https://doi.org/10.71252/2177-34912025720013
ISSN: 2177-3491

Quizalofop tank mixtures for control the main paddy rice weeds occurring in Southern Brazil

Diego Martins Chiapinotto[2], *Luis Antonio de Avila*[3], *Gustavo Vianna Junkes*[2], *Carlos Eduardo Schaedler*[4], *Bianca Camargo Aranha*[2], *Vívian Ebeling Viana*[2] *and Edinalvo Rabaioli Camargo*[2*]

[1] This study comprises a chapter of a thesis published confidentially and is not accessible to the general public.

[2] Universidade Federal de Pelotas, Faculdade de Agronomia Eliseu Maciel, Department of Crop Protection, Pelotas, RS, Brazil. dchiapinotto.dc@gmail.com; gustavo_junkes@yahoo.com.br; biancacamargoaranha@gmail.com; vih.viana@gmail.com

[3] Mississippi State University, Department of Soil and Crop Sciences, Mississippi, MS, United States of America. luis.avila@pss.msstate.edu

[4] Instituto Federal Sul-riograndense de Educação, Ciência e Tecnologia, Department of Crop Protection, Pelotas, RS, Brazil. caduschaedler@gmail.com

*Corresponding author: edinalvo_camargo@yahoo.com.br

Editors:
Danielle Fabíola Pereira da Silva
Ricardo Alcántara de la Cruz

Submitted: November 11th, 2024.
Accepted: March 2nd, 2025.

ABSTRACT

Quizalofop-p-ethyl is used in Provisia™ rice for selecive grass weed control. In southern Brazil, other weeds occur, and an herbicide tank mix is needed to achieve a broad spectrum. This study aimed to evaluate the interaction of quizalofop-p-ethyl with other herbicides used to control the main paddy rice weeds occurring in Southern Brazil. Two greenhouse experiments were performed using *Aeschynomene denticulata* Rudd (jointvetches), *Cyperus iria* L. (rice flatsedge), *Echinochloa crus-galli* L. (barnyard grass), and *Oryza* spp. (weedy rice). The factorial arrangement to each species comprises: Factor A) Doses of quizalo-fop-p-ethyl (g ha^{-1}): 0, 120, and 120 plus 120 (applied 14 days after the initial treatment - DAIT); Factor B) Tank mix partner: bentazon (960 g ha^{-1}), florpyrauxifen-benzyl (30 g ha^{-1}), quinclorac (375 g ha^{-1}), saflufenacil (30 g ha^{-1}), and control. At 42 DAIT, control and shoot dry weight (SDW) were evaluated. Colby's method compared treatments using Tukey's HSD and tank mix. No herbicide tank mix reduced or increased the variables evaluated compared to the herbicides applied alone, suggesting a neutral effect. Between the mixtures, in terms of spectrum of weed control, quizalofop-p-ethyl plus florpyrauxifen-benzyl was the best treatment, providing effective control or SDW reduction (≥ 90%) in all tested species.

Keywords: bentazone, quinclorac, Provisia™, saflufenacil, tank mix.

INTRODUCTION

The weedy rice (*Oryza* spp.)[1] is one of the most troublesome and persistent weed in directed-seeded paddy rice in America, Asia, and Europe.[2-4] Due to the weedy rice is conspecific with cultivated rice (*Oryza sativa* L.)[2], the selective control of this weed only became possible with the release of imidazolinone (IMI)-resistant rice (in the early 2000s), known as the Clearfield® production system for rice.[5] However, with the evolution of IMI-resistant weedy rice, this system became inefficient in weedy rice management.[3] Recently, Provisia™ rice system was commercialized as an alternative and complement to rice fields that use Clearfield® rice.[6]

Provisia™ rice was developed through a mutation in the gene coding for the enzyme acetyl-CoA carboxylase (ACCase), which confers resistance to quizalofop-p-ethyl (QPE) – an ACCase-inhibiting herbicide belonging to the aryloxyphenoxypropionate group.[7,8] The ACCase-inhibiting herbicides are used only against grass weeds.[9] Indeed, using QPE in Provisia™ rice allows the efficient and selective post-emergence control of IMI-resistant and -susceptible weedy rice and other grasses in paddy rice, such as *Echinochloa* spp..[9-11]

In Southern Brazil, an important producing region, other weed species belonging to the Fabaceae (*Aeschynome* spp.) and Cyperaceae (C*yperus* spp.) families occur – threatening the rice grain yield potential.[12] In *Cyperus* spp. QPE is not effective[13], and due to the evolution of resistance to ALS-inhibiting herbicides[12], the alternative has been with bentazon – a Photosystem II (PSII)-inhibiting herbicide.[14] Due to the inefficiency of ACCase-inhibiting herbicides in controlling eudicotyledonae species, an alternative is synthetic auxins.[15] Thus, an herbicide tank mix is necessary.[16]

Herbicide tank mix with different mechanisms of action is vital for rice production, providing a broad spectrum of weed control.[11] However, the tank mix can present three response patterns: neutral, synergistic, or antagonistic.[17] Additive or neutral responses occur when the weed control of the herbicide mixture is not different from the expected control of the herbicides applied alone. On the other hand, when the tank mix results in an increase or decrease in weed control, synergism or antagonism occurs respectively.[18] The mixture of QPE plus some synthetic auxins may result in an antagonistic response in weedy rice and *Echinochloa* spp. control.[11,16] The same response pattern was observed with PSII-inhibiting herbicides as the propanil.[19] Thus, selecting a tank mix partner is crucial to avoid chemical management failures.

An alternative to control broadleaf weeds can be saflufenacil, a Protoporphyrinogen IX oxidase (PPO)-inhibiting herbicide selective to rice crops.[20] Florpyrauxifen-benzyl, a synthetic auxin, which is used in the post-emergence of mono and broadleaf weeds,[21,22] constitutes another alternative due to no antagonistic effects were shown when in a tank mix with herbicides usually used on rice.[23] Furthermore, some strategies, such as the sequential application of QPE, recommended in Provisia™ rice for grass control,[16] ensure weedy rice and *Echinochloa* spp. control after application (tank mix), i.e., shown additive or neutral response.[10]

Given the history of antagonism of ACCase-inhibiting herbicides in tank mix,[10,11,16,19] it is important to evaluate interactions of QPE with other herbicides used in paddy rice. This information can contribute to weed management strategies in areas that adopt the Provisia™ rice system. This study aimed to evaluate the interaction of QPE with other herbicides used to control the main paddy rice weeds occurring in Southern Brazil.

MATERIALS AND METHODS

Location and Characterization of the Experiment

Seedlings of *Aeschynomene denticulata* Rudd (AESDE – jointvetches), *Cyperus iria* L. (CYPIR – rice flatsedge), *Echinochloa crus-galli* (L.) P. Beauv. (ECHCR – barnyard grass), and *Oryza* spp. (WR – weedy rice), were used. The seedlings used were from the seedbank belonging to the Weed Science Research Group (CEHERB – UFPel).

Two greenhouse experiments (31°48’04.2’’S, 52°24’40.8’’W) were performed in a completely randomized design with four repetitions. The treatments to each weed species comprised a two-factor scheme (3 x 5, totaling 15 treatments): A) Doses of quizalofop-p-ethyl (g ha^{-1}): 0, 120, and 120 plus 120 (applied 14 days after the initial treatment - DAIT); and B) Tank mix partner: bentazon (960 g ai ha^{-1} – Basagran®, 600 g ai L^{-1}, CS), florpyrauxifen-benzyl (30 g ai ha^{-1} - Loyant®, 25 g ai L^{-1}, EC), quinclorac (375 g ai ha^{-1} – Facet®, 500 g ai kg^{-1}, WP), saflufenacil (30 g ai ha^{-1} - Heat®, 700 g ai kg^{-1}, WP), and control (without tank mix). Application of tank mix partner herbicides ocurred only in the first application of quizalofop. The second application, for the treatments that had received, were only with quizalofop. Any treatments with quizalofop contained adjuvant at 1% v v^{-1} (Assist®, 756 g L^{-1}, EC). When applied alone, bentazon, quinclorac, and saflufenacil contained the same adjuvant at 0.5 % v v^{-1}.

In October 2021, the weed species seeds were sown in 0.7 L plastic pots containing commercial substrate. When the seedlings were at the one-leaf, they were thinned, keeping one plant per pot. When the plants reached 3-4 leaves, the treatments were applied with a CO_2 pressurized sprayer equipped with flat fan nozzles (XR 110.015 model, 0.5 m apart). The application was performed at 250 kPa working pressure, delivering 150 L ha^{-1} of carrier volume. Nozzles were positioned at 0.5 m from the top of the leaves. Pots were watered daily. Two days after the chemical treatment, a 3 cm permanent flood was established. The pots were drained one day before the second application, and the flood was restored two days later. In November 2022, the experiment was repeated, following the same factorial scheme and procedures. During the applications, the environmental conditions were monitored (digital Kestrel® 4500 Weather Meter), and the treatments occurred with temperatures between 20-25 °C, relative humidity between 68-75%, and wind speed between 3.6 and 5.1 Km ha^{-1}.

At 28 (data not shown) and 42 days after the initial quizalofop treatment, a visual evaluation was performed[10] based on a percentage scale, where 0% indicated no control and 100 % denoted total plant death. The remaining plants were cut close to the ground and placed in a forced-air oven at 60 °C until they reached a constant weight – to determine the shoot dry weight (SDW).

Data analysis

Visual estimates of control and SDW (% relative to the nontreated control) for each weed were analyzed using the R program.[(24)] The variance homogeneity and normally distributed measurement errors were evaluated by the distribution of residuals against the fitted value and normal q-q plot, illustrating whether the residuals were normally distributed, respectively. The data were transformed ($yt = \sqrt{(y + 0.5)}$) to normalize their distribution. They were submitted to multi-factor ANOVA ($p < 0.05$) to distinguish treatments and years using *aov* and *summary* functions.[(25)] Each tank mix partner was also evaluated within each quizalofop dose. Data were combined over the years, as no significant treatment-by-year interaction existed. When the treatments were significant, the means were separated using Tukey's Honestly Significant Difference test (Tukey's HSD; $\alpha = 0.05$).

The control (%) and SDW reduction (% relative to the nontreated control) were submitted to the Colby equation to evaluate the tank mix interactions (Equation 1). The Mann-Whitney U Test was used to compare the values of the expected response of the tank mix with the observed response of the herbicide applied alone ($p < 0.05$). Tank mixes were considered antagonistic when the observed value was significantly lower than the expected value, additive if there was no difference between the values, and synergistic if the observed value was higher than the predicted value.[(17)]

$$E = (A + B) - (A * B)/100 \qquad \text{(Equation 1)}$$

where E is the expected value for the herbicide mixture, with A and B being the observed value for each herbicide applied alone.

RESULTS AND DISCUSSION

For both control and SDW reduction, Colby's method showed that no herbicide tank mix reduced or increased the variables evaluated compared to the herbicides applied alone – showing a neutral response pattern (Tables 1 and 2). Regarding the different chemical treatments, for AESDE, florpyrauxifen-benzyl or saflufenacil applied alone or in a tank mix with QPE were effective, that is, control or reduction of MSPA ≥ 90%[(16)] (Figures 1A and 2A). For CYPIR, bentazon and florpirauxifen alone or mixed with QPE were effective (Figures 1B and 2B). For ECHCR, florpiraxifen-benzyl, quinclorac, or QPE alone or in a tank mix were effective (Figures 1C and 2C). For weedy rice, QPE alone or in a mixture with all other herbicides was effective (Figures 1D and 2D). The tank mix of QPE plus florpirauxifen was highlighted in the effective control of all species evaluated.

The use of quizalofop-p-ethyl in Provisia™ rice allows efficient and selective post-emergence control of weedy rice and other grasses, such as *Echinochloa* spp. at the 2–3-leaf stage.[(9-11)] The results of this study confirm the high efficiency of QPE in controlling these species. However, when QPE was applied alone, as expected due to its lack of activity on sedges and eudicotyledonae species,[(13,16,26)] it was not efficient in controlling AESDE and CYPIR, requiring herbicide tank mix.

In the present study, bentazon efficiently controlled

CYPIR, with results like those of Chiapinotto and the collaborators.[14] It did not affect the weed control when applied in a mixture with QPE. A neutral response pattern was also reported in the control of weedy rice and *Echinochloa* spp. with QPE plus bentazon tank mix.[19] Certain PSII-inhibiting herbicides, which bind to the plastoquinone B (QB) binding site of the D1 protein and interrupt the photosynthetic transport of electrons from QA to QB,[27] such as propanil, can interact with esterases found in the apoplast – affecting the conversion of ACCase inhibitor herbicides to the acidic form and reducing control of the target weed.[28] Bentazon, on the other hand, can reduce the activity of plasma membrane ATPases and reduce weed control,[29] explaining the antagonism observed in the mixture with sethoxydim. However, the pattern of antagonistic response to the tank mix depends on the weed evaluated.[19]

Synthetic auxins are used as herbicides, mainly in managing broadleaves weeds.[15] However, as an inducer of

Table 1. Control (% of nontreated control) on the weed (AESDE = *Aeschynomene denticulata*, CYPYR = *Cyperus iria*, ECHCR = *Echinochloa crus-galli*, and WR = *Oryza* spp. – weedy rice) as affected by tank mix of quizalofop-p-ethyl with herbicides used in paddy rice at 42 days after initial treatment

AESDE		**Quizalofop-p-ethyl (g ai ha^{-1})**						
		0	120			120; 120		
Tank mix	g a.i ha^{-1}	Observed[1]	Observed	Expected	p-value[2]	Observed	Expected	p-value[2]
None	-	0.00	0.00	0.00	-	4.25	0.00	-
Bentazon	960	3.87	4.37	3.87	0.83	7.75	7.95	0.94
Florpirauxifen	20	98.75	98.75	98.75	1.00	98.75	98.80	1.00
Quinclorac	375	84.37	88.75	84.37	0.07	87.50	85.03	0.52
Saflufenacil	30	98.87	98.75	98.87	1.00	98.75	98.92	0.72
CYPIR		Quizalofop-p-ethyl (g ai ha^{-1})						
		0	120			120; 120		
Tank mix	g a.i ha^{-1}	Observed[1]	Observed	Expected	p-value[2]	Observed	Expected	p-value[2]
None	-	0.00	0.00	-	-	0.00	-	-
Bentazon	960	98.75	98.50	98.75	1.00	98.75	98.75	1.00
Florpirauxifen	20	90.25	90.00	90.25	0.94	93.87	90.25	0.14
Quinclorac	375	1.25	1.00	1.25	0.35	1.50	1.25	0.83
Saflufenacil	30	2.75	2.37	2.75	0.52	3.12	2.75	0.83
ECHCR		Quizalofop-p-ethyl (g ai ha^{-1})						
		0	120			120; 120		
Tank mix	g a.i ha^{-1}	Observed[1]	Observed	Expected	p-value[2]	Observed	Expected	p-value[2]
None	-	0.00	99.25	-	-	99.12	-	-
Bentazon	960	21.87	98.75	99.41	0.28	98.62	99.31	0.28
Florpirauxifen	20	95.37	97.12	99.96	0.29	99.00	99.96	0.29
Quinclorac	375	99.00	98.62	99.99	0.26	98.87	99.99	0.71
Saflufenacil	30	28.12	99.00	99.46	0.43	99.00	99.36	0.35
WR		Quizalofop-p-ethyl (g ai ha^{-1})						
		0	120			120; 120		
Tank mix	g a.i ha^{-1}	Observed[1]	Observed	Expected	p-value[2]	Observed	Expected	p-value[2]
None	-	0.00	98.50	-	-	98.62	-	-
Bentazon	960	1.25	97.62	98.52	0.72	98.87	98.64	0.94
Florpirauxifen	20	1.75	98.37	98.52	0.72	98.75	98.64	0.82
Quinclorac	375	0.75	98.62	98.51	0.94	99.00	98.63	0.43
Saflufenacil	30	0.75	97.50	98.51	0.71	98.62	98.63	0.52

[1] Values observed and expected, according with the Colby method, in order to estimate the putative joint action of mixtures (expected = observed, additivity; expected > observed, antagonism; expected < observed, synergism). [2] p-value > 0.05 denotes no difference between the observed and expected values, i.e., additive or neutral response pattern.

P450s, 2,4-dichlorophenoxyacetic acid (2,4-D) promotes the transformation of acidic FOPs into non-toxic polar metabolites in pretreated plants compared to untreated plants, which reduces the efficacy of ACCase herbicides.[30] Quinclorac, which also controls grasses,[31] is related to increased transcription of P450s enzymes.[32] Thus, when in a tank mix with QPE, it can result in reduced control of ECHCR[11] and weedy rice[16] or present a neutral response pattern.[11,16]

In the present study, QPE plus quinclorac efficiently controlled ECHCR and weedy rice, presenting a neutral response pattern and broadening the control spectrum. The divergent results mentioned above may be related to intraspecific variations in *E. crus-galli* that confer different levels of herbicide susceptibility.[33] The same occurs with weedy rice, where this mixture can reduce[16] or not affect[11] control. Therefore, caution should be exercised when using this herbicide tank mix.

Table 2. Dry wight reduction (% of nontreated control) on the weed shoot (AESDE = *Aeschynomene denticulata*, CYPYR = *Cyperus iria*, ECHCR = *Echinochloa crus-galli*, and WR = *Oryza* spp. – weedy rice) as affected by tank mix of quizalofop-p-ethyl with herbicides used in paddy rice at 42 days after initial treatment

AESDE		**Quizalofop-p-ethyl (g ai ha^{-1})**						
		0	120			120; 120		
Tank mix	g a.i ha^{-1}	Observed[1]	Observed	Expected	p-value[2]	Observed	Expected	p-value[2]
None	-	0.00	0.00	-	-	-	0.00	-
Bentazon	960	3.67	2.99	3.67	0.84	2.76	3.67	1.00
Florpirauxifen	20	97.25	97.63	97.25	0.38	97.89	97.25	0.11
Quinclorac	375	79.15	78.24	79.15	0.74	83.08	79.15	0.19
Saflufenacil	30	96.37	97.59	96.37	0.19	97.65	96.37	0.19
CYPIR		Quizalofop-p-ethyl (g ai ha^{-1})						
		0	120			120; 120		
Tank mix	g a.i ha^{-1}	Observed[1]	Observed	Expected	p-value[2]	Observed	Expected	p-value[2]
None	-	0.00	0.00	-	-	0.00	-	-
Bentazon	960	98.94	99.13	98.94	0.61	98.95	98.94	1.00
Florpirauxifen	20	90.07	90.97	90.07	0.46	91.66	90.07	0.38
Quinclorac	375	3.53	3.12	3.53	0.94	3.59	3.53	0.74
Saflufenacil	30	8.91	12.10	8.91	0.54	12.62	8.91	0.38
ECHCR		Quizalofop-p-ethyl (g ai ha^{-1})						
		0	120			120; 120		
Tank mix	g a.i ha^{-1}	Observed[1]	Observed	Expected	p-value[2]	Observed	Expected	p-value[2]
None	-	0.00	97.49	-	-	97.96	-	-
Bentazon	960	6.43	97.64	97.65	1.00	97.80	98.09	0.46
Florpirauxifen	20	95.98	97.56	99.89	0.71	98.61	99.91	0.28
Quinclorac	375	97.37	98.20	99.93	0.29	98.55	99.95	0.29
Saflufenacil	30	18.65	97.54	97.95	0.46	97.72	98.34	0.11
WR		Quizalofop-p-ethyl (g ai ha^{-1})						
		0	120			120; 120		
Tank mix	g a.i ha^{-1}	Observed[1]	Observed	Expected	p-value[2]	Observed	Expected	p-value[2]
None	-	0.00	92.45	-	-	94.78	-	-
Bentazon	960	0.88	93.18	92.52	0.38	95.24	94.82	0.54
Florpirauxifen	20	3.82	92.89	92.73	0.94	95.53	94.98	0.74
Quinclorac	375	5.14	94.42	92.84	0.10	94.94	95.05	0.84
Saflufenacil	30	0.00	92.45	92.45	0.94	94.36	94.78	0.64

[1] Values observed and expected, according with the Colby method, in order to estimate the putative joint action of mixtures (expected = observed, additivity; expected < observed, antagonism; expected > observed, synergism). [2] p-value ≥ 0.05 denotes no difference between the observed and expected values, i.e., additive or neutral response pattern.

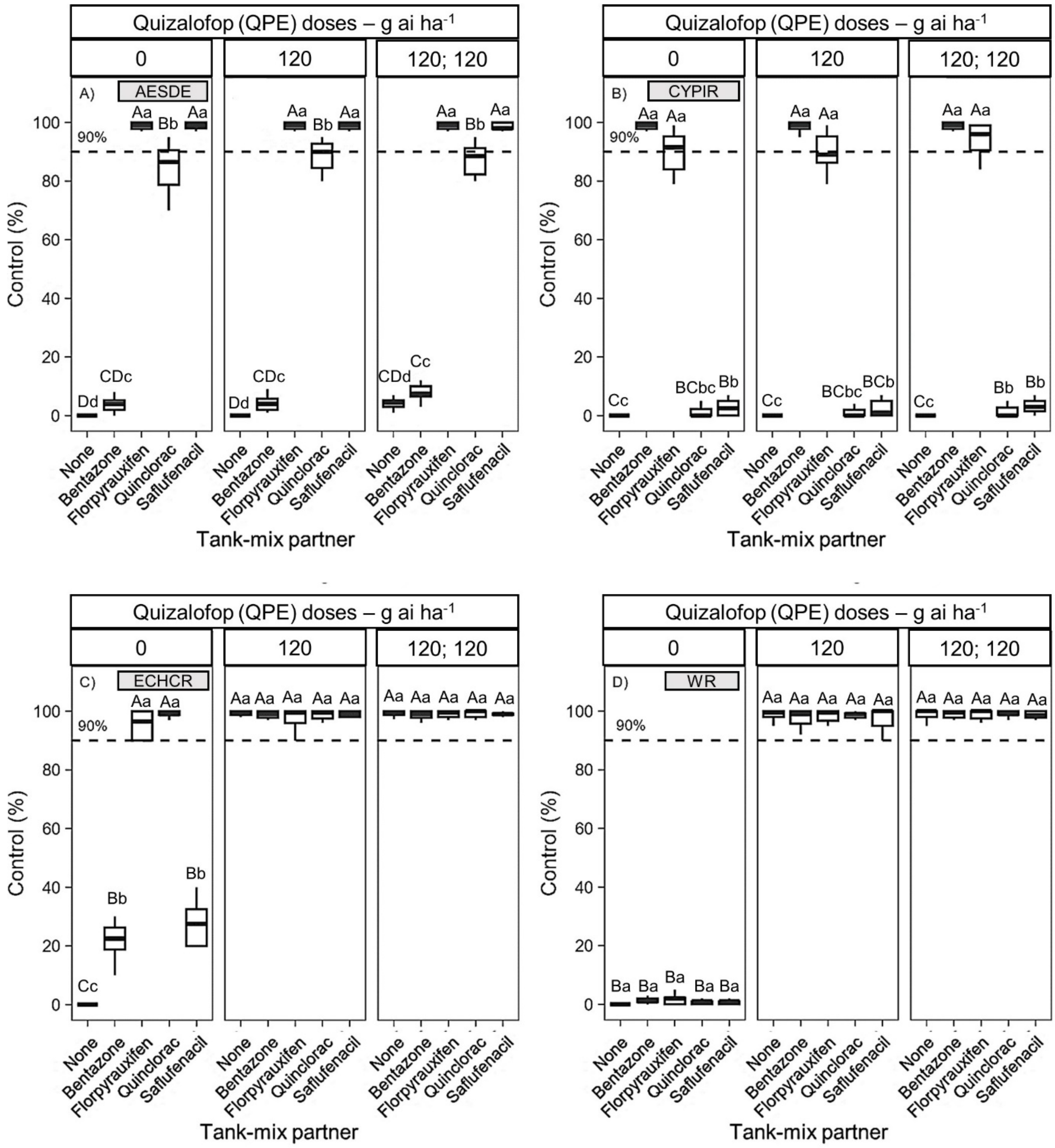

Figure 1. Control (% of nontreated control) on the weed (AESDE = *Aeschynomene denticulata*, CYPYR = *Cyperus iria*, ECHCR = *Echinochloa crus-galli*, and WR = *Oryza* spp. – weedy rice) as affected by quizalofop-p-ethyl (QPE), applied alone or in tank mix with herbicides used in paddy rice, at 42 days after initial treatment. Means values with uppercase compare the treatments and lowercase compare tank mix partner within each QPE dose. Treatment means, followed by different letters, differ from each other by Tukey's HSD test (α=0.05).

It is also known that quinclorac is effective in controlling *Aeschynomene* spp..[34] The genus *Aeschynome*, a word that in Greek means "shy" or "ashamed," includes plants that are sensitive to touch, and the leaves can close in certain situations,[35] which can reduce foliar absorption. Quinclorac has greater absorption by plant roots.[36] However, herbicide adsorption increases with increased cation exchange capacity (CEC), making the molecule less bioavailable.[37] Therefore, a commercial substrate with high CEC may have reduced the herbicide efficiency, justifying control below 90% in AESDE.

Florpirauxifen-benzyl, a new auxin-type herbicide,[23] is used to control mono- (including *Cyperus* spp.) and eudicotyledons weeds.[21,22,38] No antagonistic effects have been reported when florpyrauxifen is tank mixed with herbicides used on rice (either contact or systemic).[23] The results of this study corroborate those mentioned previously, indicating that QPE plus florpyrauxifen efficiently controlled all weed species evaluated. Florpirauxifen is selective to rice.[39] However, herbicide tank mix can reduce the grain yield of rice crops, requiring field studies to assess selectivity.[40] Furthermore, continuous use of florpyrauxifen can select herbicide-resistant weeds and should be avoided.[41,42]

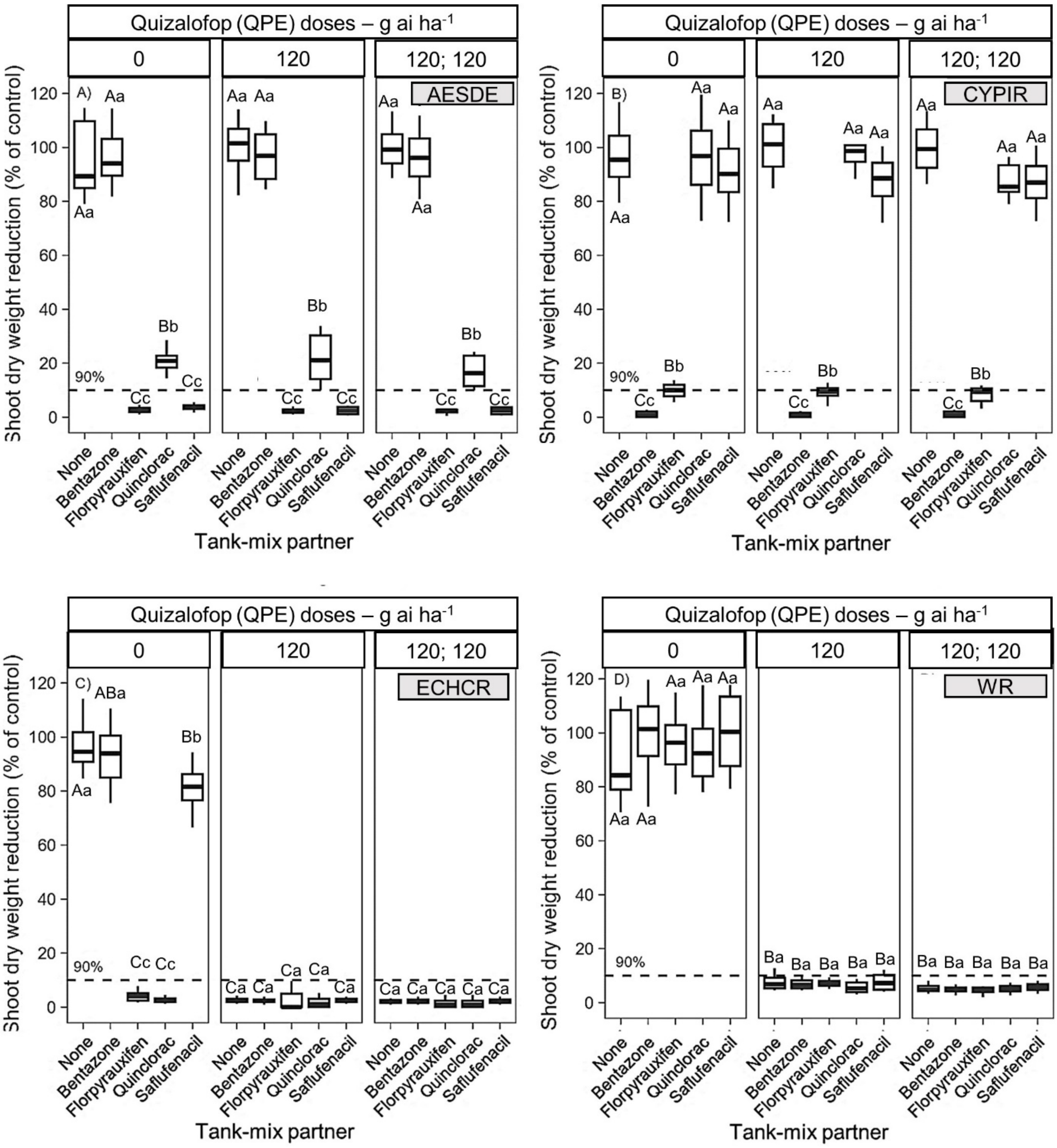

Figure 2. Shoot dry weight reduction (% of nontreated control) on the weed (AESDE = *Aeschynomene denticulata*, CYPYR = *Cyperus iria*, ECHCR = *Echinochloa crus-galli*, and WR = *Oryza* spp. – weedy rice) as affected by quizalofop-p-ethyl (QPE), applied alone or in tank mix with herbicides used in paddy rice, at 42 days after initial treatment. Means values with uppercase compare the treatments and lowercase compare tank mix partner within each QPE dose. Treatment means, followed by different letters, differ from each other by Tukey's HSD test (α=0.05).

The combination of ACCase and PPO inhibitor herbicides for activity on grasses has often been reported as antagonistic.[18] Most foliar herbicides must be retained and deposited on the surface of the target weed plant, penetrate the cell, and reach the target site in sufficient quantities – where they bind and result in plant death.[43] Due to reduced translocation, contact herbicides can inhibit the effectiveness of systemic herbicides.[44]

PPO inhibitor herbicides are considered contact, have rapid foliar activity, and have a restricted spectrum of control for broadleaf weeds.[45] However, saflufenacil is absorbed by the roots and shoots. Due to its weak acidity, this herbicide is distributed systemically inside the plant through acropetal and basipetal movement.[46] A neutral control pattern with QPE plus saflufenacil, like that found in this study, was reported in the control of weedy rice and *Echinochloa* spp..[19] Similar results were obtained with saflufenacil and imazapyr + imazapic.[40]

Tank mixing herbicides can present different responses in controlling weeds, making evaluating the effects on target weeds crucial. The results of this study suggest that bentazon, florpirauxifen-benzil, quinclorac, and saflufenacil have potential use with QPE in Provisia™ rice, increasing the control spectrum of the main paddy rice weeds occurring in southern Brazil. However, field studies are recommended to evaluate the selectivity of mixtures on paddy rice conditions and grain yield.

CONCLUSION

This study evaluated the effectiveness of chemical weed management in paddy rice using herbicide tank mixtures to broaden the control spectrum, especially when using new ACCase-resistant rice technologies. The tank mix of quizalofop plus florpyrauxifen-benzyl can potentially control the main paddy rice weeds in southern Brazil. However, field studies are recommended to evaluate the selectivity of mixtures on paddy rice conditions and grain yield. The results demonstrated potential for use in Provisia™ rice system.

DATA AVAILABILITY

The datasets used during the current study are available from the corresponding author on reasonable request.

ACKNOWLEDGEMENTS

We thank the Weed Science Research Group (CEHERB – UFPel) for the support and discussions of this research. This study was supported in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Finance Code 001; and by the Conselho Nacional de Pesquisa (CNPq) via the research fellowships for process no. 426714/2018-0 and process no. 311449/2022-0. The first author is a CNPq doctoral fellowship. We have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Bianca Camargo Aranha, Carlos Eduardo Schaedler, Diego Martins Chiapinotto, Edinalvo Rabaioli Camargo, Gustavo Vianna Junkes, Luis Antonio de Avila, Vívian Ebeling Viana.

Data curation: Bianca Camargo Aranha, Diego Martins Chiapinotto.

Formal analysis: Diego Martins Chiapinotto.

Funding acquisition: Edinalvo Rabaioli Camargo, Luis Antonio de Avila.

Investigation: Diego Martins Chiapinotto, Edinalvo Rabaioli Camargo.

Methodology: Diego Martins Chiapinotto, Edinalvo Rabaioli Camargo.

Project administration: Carlos Eduardo Schaedler, Diego Martins Chiapinotto, Edinalvo Rabaioli Camargo, Luis Antonio de Avila.

Resources: Edinalvo Rabaioli Camargo, Luis Antonio de Avila.

Software: Diego Martins Chiapinotto.

Supervision: Carlos Eduardo Schaedler, Edinalvo Rabaioli Camargo, Luis Antonio de Avila.

Validation: Diego Martins Chiapinotto, Edinalvo Rabaioli Camargo, Luis Antonio de Avila.

Visualization: Diego Martins Chiapinotto, Edinalvo Rabaioli Camargo.

Writing – original draft: Bianca Camargo Aranha, Diego Martins Chiapinotto, Edinalvo Rabaioli Camargo.

Writing – review & editing: Bianca Camargo Aranha, Carlos Eduardo Schaedler, Diego Martins Chiapinotto, Edinalvo Rabaioli Camargo, Gustavo Vianna Junkes, Luis Antonio de Avila, Vívian Ebeling Viana.

REFERENCES

1. Roma-Burgos N, San Sudo MP, Olsen KM, Werle I, Song BK. Weedy rice (Oryza spp.): what's in a name? Weed Sci. 2021;69(5):505-13.
2. Zhang Z, Dai W, Song X, Qiang S. A model of the relationship between weedy rice seed-bank dynamics and rice-crop infestation and damage in Jiangsu Province, China. Pest Manag Sci.

2013;70(5):716-24.

3. Merotto A, Goulart ICGR, Nunes AL, Kalsing A, Markus C, Menezes VG, et al. Evolutionary and social consequences of introgression of nontransgenic herbicide resistance from rice to weedy rice in Brazil. Evol Appl. 2016;9(7):837-46.

4. Dai L, Song X, He B, Valverde BE, Qiang S. Enhanced photosynthesis endows seedling growth vigour contributing to the competitive dominance of weedy rice over cultivated rice. Pest Manag Sci. 2017;73(7):1410-20.

5. Sudianto E, Beng-Kah S, Ting-Xiang N, Saldain NE, Scott RC, Burgos NR. Clearfield® rice: Its development, success, and key challenges on a global perspective. Crop Prot. 2013;49:40-51.

6. Dauer J, Hulting A, Carlson D, Mankin L, Harden J, Mallory-Smith C. Gene flow from single and stacked herbicide-resistant rice (Oryza sativa): modeling occurrence of multiple herbicide-resistant weedy rice. Pest Manag Sci. 2017;74(2):348-55.

7. Famoso AN, Harrell DL, Groth DE, Webster EP, Oard JH, Zaunbrecher RE, et al. Registration of "PVL01" Rice. J Plant Regist. 2019;13(3):330-3.

8. Camacho J, Linscombe SD, Sanabria Y, Mosquera PA, Oard JH. Inheritance of Provisia™ rice resistance to quizalofop-p-ethyl under laboratory and greenhouse environments. Euphytica. 2019;215(4):1-9.

9. Lancaster ZD, Norsworthy JK, Scott RC. Evaluation of Quizalofop-Resistant Rice for Arkansas Rice Production Systems. Int J Agron. 2018;1-8.

10. Rustom SY, Webster EP, Blouin DC, McKnight BM. Interactions Between Quizalofop-p-ethyl and Acetolactate Synthase–Inhibiting Herbicides in Acetyl-coA Carboxylase Inhibitor–Resistant Rice Production. Weed Technol. 2018;32(3):297-303.

11. Webster EP, Rustom SY, McKnight BM, Blouin DC, Teló GM. Quizalofop-p-ethyl mixed with synthetic auxin and ACCase-inhibiting herbicides for weed management in rice production. Int J Agron. 2019;1-7.

12. Ulguim R, Silva B, Agostinetto D, Andrade Neto RC, Zandoná RR. Resistance mapping of the genus Cyperus in Rio Grande do Sul and selection pressure analysis. Planta Daninha. 2019;37:e019188242.

13. Yadav R, Bhullar MS, Kaur S, Kaur T, Jhala AJ. Weed control in conventional soybean with pendimethalin followed by imazethapyr plus imazamox/quizalofop. Canadian Journal of Plant Science. 2017;97(4):654-64.

14. Chiapinotto DM, Schaedler CE, Lamego FP, Andres A, Tambara AL, Jaskulski WL. Alternativas de controle químico de junquinho resistente aos herbicidas inibidores da ALS. Rev Bras Herbicidas. 2019;18(2):1-7.

15. Song Y. Insight into the mode of action of 2,4-dichlorophenoxyacetic acid (2,4-D) as an herbicide. J Integr Plant Biol. 2014;56(2):106-13.

16. Lancaster ZD, Norsworthy JK, Scott RC, Gbur EE, Norman RJ. Evaluation of quizalofop tank-mixtures for quizalofop-resistant rice. Crop Prot. 2019;116:7-14.

17. Colby SR. Calculating synergistic and antagonistic responses of herbicide combinations. Weeds. 1967;15(1):20-2.

18. Barbieri GF, Young BG, Dayan FE, Streibig JC, Takano HK, Merotto A, et al. Herbicide mixtures: interactions and modeling. Adv Weed Sci. 2022;40:e02200702.

19. Rustom SY, Webster EP, Blouin DC, McKnight BM. Interactions of quizalofop-p-ethyl mixed with contact herbicides in ACCase-resistant rice production. Weed Technol. 2019;33(2):233-8.

20. Camargo ER, Senseman SA, McCauley GN, Guice JB. Rice tolerance to saflufenacil in clomazone weed control program. Int J Agron. 2011;1-8.

21. Epp JB, Alexander AL, Balko TW, Buysse AM, Brewster WK, Bryan K, et al. The discovery of Arylex™ active and Rinskor™ active: two novel auxin herbicides. Bioorg Med Chem. 2016;24(3):362-71.

22. Johnson P. Development of a novel route for incorporation of carbon-14 into the pyridine ring of Rinskor active. Org Process Res Dev. 2019;23(10):2243-52.

23. Miller MR, Norsworthy JK. Florpyrauxifen-benzyl weed control spectrum and tank-mix compatibility with other commonly applied herbicides in rice. Weed Technol. 2018;32(3):319-25.

24. R Core Team. R: The R Project for Statistical Computing. R-project.org [Internet]. 2021 [cited 2024 Jul 31]. Available from: https://www.r-project.org/

25. Kniss A, Streibig J. Statistical analysis of agricultural experiments using R. Rstats4ag.org [Internet]. 2019 [cited 2024 Jul 31]. Available from: https://www.rstats4ag.org/

26. Shaner DL. Lessons learned from the history of herbicide resistance. Weed Sci. 2014;62(2):427-31.

27. Battaglino B, Grinzato A, Pagliano C. Binding properties of photosynthetic herbicides with the QB site of the D1 protein in plant Photosystem II: a combined functional and molecular docking study. Plants (Basel). 2021;10(8):1501.

28. Ottis BV, Mattice JD, Talbert RE. Determination of antagonism between cyhalofop-butyl and other rice (Oryza sativa) herbicides in barnyardgrass (Echinochloa crus-galli). J Agric Food Chem. 2005;53(10):4064-8.

29. Couderchet M, Retzlaff G. The role of the plasma membrane ATPase in bentazone-sethoxydim antagonism. Pest Sci. 1991;32(3):295-306.

30. Han H, Yu Q, Cawthray GR, Powles SB. Enhanced herbicide metabolism induced by 2,4-D in herbicide-susceptible Lolium rigidum provides protection against diclofop-methyl. Pest Manag Sci. 2013;69(9):996-1000.

31. Grossmann K. Auxin herbicides: current status of mechanism and mode of action. Pest Manag Sci. 2009;65(10):1023-8.

32. Xu W, Di C, Zhou S, Liu J, Li L, Liu F, et al. Rice transcriptome analysis to identify possible herbicide quinclorac detoxification genes. Front Genet. 2015;6:306.

33. Lopez-Martinez N, Salvá AP, Finch RP, Marshall G, De Prado R. Molecular markers indicate intraspecific variation in the control of Echinochloa spp. with quinclorac. Weed Sci. 1999;47(3):310-5.

34. Fleck NG, Lazaroto CA, Schaedler CE, Ferreira FB. Susceptibility of three jointvetch species (Aeschynomene spp.) to herbicides used in postemergence in flooded rice. Rev Bras Agrociênc. 2008;14:77-86.

35. Dornelles SHB. Control Aeschynomene denticulata in post-late along with the application of fungicide in rice cultivation. Vivências. 2014;10:42-9.

36. Concenço G, Silva AF, Ferreira EA, Galon L, Noldin JÁ, Aspiazú L, Ferreira FA, Silva AA. Effect of dose and application site on quinclorac absorption by barnyardgrass biotypes. Planta Daninha. 2009;27:541-8.

37. Mendes KF, Silva R, Takeshita V, Jiménez F, Paula A, Tornisielo VL. Cow bone char as a sorbent to increase sorption and decrease mobility of hexazinone, metribuzin, and quinclorac in soil. Geoderma. 2019;343:40-9.

38. Bundt ADC, Morel M, Neves R. Introdução do Rinskor™ como ferramenta para manejo químico de capim-arroz resistente à ALS. Braz J Dev. 2019;5(11):24502-9.

39. Velásquez JC, Bundt ADC, Camargo ER, Andres A, Viana VE, Hoyos V, et al. Florpyrauxifen-benzyl selectivity to rice. Agriculture. 2021;11(12):1270.

40. Feijó ÂR, Fipke MV, Silveira LP, Camargo ER, Kruse ND, Avila LA. Interaction between saflufenacil and imazapyr+imazapic in the management of barnyardgrass and weedy rice and selectivity for irrigated rice. Ciênc Rural. 2020;50(7):e20190732.

41. Hwang J, Norsworthy JK, González-Torralva F, Priess GL, Barber LT, Butts TR. Non-target-site resistance mechanism of barnyardgrass (Echinochloa crus-galli L. P. Beauv.) to florpyrauxifen-benzyl. Pest Manag Sci. 2021;78(1):287-95.

42. Takano HK, Greenwalt S, Ouse D, Zielinski M, Schmitzer P. Metabolic cross-resistance to florpyrauxifen-benzyl in barnyardgrass (Echinochloa crus-galli) evolved before the commercialization of Rinskor™. Weed Sci. 2023;71(2):77-83.

43. Délye C, Jasieniuk M, Le Corre V. Deciphering the evolution of herbicide resistance in weeds. Trends Genet. 2013;29(11):649-58.

44. Castner MC, Norsworthy JK, Barber LT, Roberts TL, Gbur EE. Interaction of contact herbicides and timing of dicamba exposure on soybean. Weed Technol. 2021;35(5):725-32.

45. Dayan FE, Watson SB. Plant cell membrane as a marker for light-dependent and light-independent herbicide mechanisms of action. Pestic Biochem Physiol. 2011;101(3):182-90.

46. Grossmann K, Hutzler J, Caspar G, Kwiatkowski J, Brommer CL. Saflufenacil (Kixor™): Biokinetic properties and mechanism of selectivity of a new protoporphyrinogen IX oxidase inhibiting herbicide. Weed Sci. 2011;59(3):290-8.