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CROP PROTECTION

Pre-emergent herbicides during the off-season of irrigated rice to control weedy rice and reduce the soil seed bank

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ABSTRACT: Weedy rice (*Oryza sativa* L.) is the most important weed in irrigated rice cultivation, being one of the main factors limiting cereal productivity in Rio Grande do Sul (RS). Thus, this study determined the effect of pre-emergent herbicide use in autumnal management on the control and reduction of the weedy rice seed bank. Field experiments were conducted in a randomized complete block design with four replications in a commercial rice production area in the 2021/22 and 2022/23 growing seasons in Dom Pedrito (RS). The scheme used was factorial, with factor A consisting of different herbicide application times, namely June, July, and August, and corresponding to 100, 78, and 26 days and 42, 26, and 10 days before rice sowing for the agricultural years 2021/22 and 2022/23, respectively. Factor B consisted of the application of the herbicides s-metolachlor (1440 g a.i. ha^{-1}), sulfentrazone + diuron (210 and 420 g a.i. ha^{-1}), piroxasulfone (170 g a.i. ha^{-1}), and flumioxazin (50 g a.i. ha^{-1}), in addition to the control (no application). The evaluated variables were control (%), number of plants (m^{-2}) at crop pre-harvest, number of full, viable, and non-viable wild rice seeds m^{-2} in the soil, crop injury (%), and grain yield (kg ha^{-1}). The herbicides showed control values below 25% and low reduction of the seed bank in the soil, being considered ineffective in this application modality. The herbicides s-metolachlor, sulfentrazone + diuron, and flumioxazin exhibited the highest injury values; however, they did not significantly affect crop productivity. Thus, when applied before rice sowing, the herbicides s-metolachlor, sulfentrazone + diuron, pyroxasulfone, and flumioxazin did not provided satisfactory control and do not significantly reduce the wild rice seed bank.
Key words: *Oryza sativa* (L.), integrated weed management, s-metolachlor, sulfentrazone + diuron, pyroxasulfone, flumioxazin.

Herbicidas pré-emergentes durante a entressafra do arroz irrigado para o controle de arroz-daninho e redução do banco de sementes

RESUMO: O arroz-daninho (*Oryza sativa* L.) é a planta daninha de maior importância na cultura do arroz irrigado, sendo um dos principais fatores que limitam a produtividade do cereal no Rio Grande do Sul (RS). Desse modo, o objetivo deste trabalho foi determinar o efeito do uso de herbicidas pré-emergentes no manejo outonal, no controle e redução do banco de sementes de arroz-daninho. Foi realizado experimento no campo em delineamento experimental de blocos casualizados com quatro repetições, em área comercial de produção de arroz nas safras agrícolas 2021/22 e 2022/23, no município de Dom Pedrito (RS). O esquema utilizado foi fatorial, cujo fator A consistiu em diferentes épocas de aplicação dos herbicidas, sendo denominadas de junho, julho e agosto, que se referem a 100, 78, 47 dias e 42, 26 e 10 dias antes da semeadura do arroz, para os anos agrícolas 2021/22 e 2022/23, respectivamente. O fator B constou da aplicação dos herbicidas s-metolachlor (1440 g i.a. ha^{-1}), sulfentrazone + diuron (210 e 420 g i.a. ha^{-1}), piroxasulfone (170 g i.a. ha^{-1}) e flumioxazin (50 g i.a. ha^{-1}), além da testemunha (sem aplicação). As variáveis avaliadas foram o controle (%), o número de plantas (m^{-2}) na pré-colheita da cultura, número de sementes cheias, viáveis e inviáveis de arroz-daninho m^{-2} no solo, além da fitotoxicidade (%) à cultura e a produtividade de grãos (kg ha^{-1}). Os herbicidas apresentaram valores de controle abaixo de 25%, e baixa redução do banco de sementes no solo, sendo considerados não eficazes nessa modalidade de aplicação. Os herbicidas s-metolaclhor, sulfentrazone + diuron e flumioxazin apresentaram os maiores valores de fitotoxicidade, entretanto não afetaram de modo significativo a produtividade da cultura. Desse modo, os herbicidas s-metolachlor, sulfentrazone + diuron, pyroxasulfone e flumioxazin, quando aplicados antes da semeadura do arroz, não apresentam controle satisfatório e não reduzem significativamente o banco de sementes do arroz-daninho.
Palavras-chave: *Oryza sativa* (L.), manejo integrado de plantas daninhas, s-metolachlor, sulfentrazone + diuron, pyroxasulfone, flumioxazin.

INTRODUCTION

Weedy rice (*Oryza sativa* L.) is one of the main weeds in irrigated rice fields in the southern region of Brazil (FRUET et al., 2019; SILVA et al., 2020), and it can compromise up to 100% of yield if left uncontrolled (KUMAR & LADHA, 2011). As the same species, weedy rice competes with cultivated rice for water, light, and nutrients, and the environmental conditions (soil and climatic) that favor cultivated rice generally also favor weedy rice. Currently, one of the main methods of weedy rice control is the use of mutant cultivars with herbicide tolerance, such as inhibitors of acetyl coenzyme-A carboxylase (ACCase) or the group of imidazolinones, with the latter defined as the Clearfield® System (CL).

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Clearfield technology is employed in over 80% of the rice-growing area in the Brazil (KALSING et al., 2019). However, with the high frequency of use and sometimes inadequate management, biotypes of weedy rice resistant to imidazolinones have been selected (GOULART et al., 2012; GOULART et al., 2014). In this regard, managing weedy rice biotypes with resistance is highly relevant, as it is crucial for the success of rice production. In Brazil, genotypes with tolerance to ACCase inhibitor herbicides were released in the 2022/2023 crop season. However, additional management alternatives must be adopted to handle resistant biotypes and mitigate the evolution of resistance to new herbicide action mechanisms.

One of the recommendations for managing resistant weed species is the use of pre-emergence herbicides. This is justified because, in general, these herbicides have mechanisms of action that are distinct from those used post-emergence (OSIPE et al., 2014), and the selection pressure for resistant biotypes to these herbicides is lower (SOMERVILLE et al., 2017). The primary benefit of using these herbicides is the control of weeds after the germination process, preventing or delaying their emergence and thus favoring the initial establishment of the crop without competition (SOMERVILLE et al., 2017). However, because weedy rice is the same species as cultivated rice, herbicides that are selective to this crop do not control weedy rice, complicating the integrated management of resistant biotypes. Therefore, an alternative is to apply pre-emergence herbicides that control weedy rice before the rice crop is established.

This management alternative is to reduce weedy rice infestation in rice production areas (NORSWORTHY et al., 2018; BERTUCCI et al., 2019). However, injury damage to rice can reach values of 100% (GODWIN et al., 2018), making its application infeasible. Nevertheless, with proper dosage adjustment and application timing, satisfactory results can be achieved. This inference can be made because the injury caused to the crop does not reduce yield to the same extent as the untreated control, which experiences reduced yield due to competition with weedy rice (LAWRENCE et al., 2018). Moreover, despite several studies evaluating the effects of pre-emergence herbicides on weedy rice control and injury to rice crops, there is limited information on their effects on the weedy rice seed bank. Characteristics such as staggered maturation, natural shattering, dormancy, and seed longevity make the management of the weedy rice seed bank difficult (AGOSTINETTO et al., 2001). Studies evaluating the viability of weedy rice seeds under different cultivation systems concluded that viable seeds were found in all management practices after 22 years (VARGAS et al., 2023). Therefore, methods that can reduce the seed bank are of fundamental importance in integrated weed management.

As mentioned previously, post-emergence control is limited since the crop and the weed are the same species. Additionally, potential pre-emergence herbicides that control weedy rice may cause injury to the crop, although they are an alternative for weedy rice management. Therefore, studies are needed to evaluate the early application of pre-emergence herbicides to control the emergence of weedy rice before sowing without causing damage to the crop. Thus, this study analyzed the impact of using pre-emergence herbicides applied during the off-season on weedy rice control and seed bank dynamics in rice production areas.

MATERIALS AND METHODS

An experiment was conducted in the field in a rice yield area in the municipality of Dom Pedrito/RS (latitude 31.01ºS and longitude 54.68ºW), repeated in the crop seasons 2021/22 and 2022/23. The soil of the site is classified as Planossolo Hidromórfico (Planosol) (STRECK et al., 2008), with characteristics of 1.1% organic matter and 48.4, 32.2, and 19.4% sand, silt, and clay, respectively. The experimental design used was a randomized complete block design, with four replications, and the experimental units were plots measuring 6 × 15 m (90 m^2) each. The areas had natural infestation of weedy rice (with 3 and 6 plants m^{-2} for the seasons 2021/22 and 2022/23, respectively), and soybean cultivation occurred in the previous seasons.

Rice cultivation in the area was carried out using the no-tillage system, meaning that there was no soil disturbance after soybean harvest. Soil fertility correction was performed by applying 200 kg ha^{-1} of 15-30-20 fertilizer at sowing and 300 kg nitrogen (N) ha^{-1} in the form of urea as topdressing in both crop seasons. For the 2021/22 season, the XP202FP hybrid, which is tolerant to herbicides from the imizadolinone chemical group (ALS inhibitors), was used. It was sown on September 23, 2021, at a density of 50 kg ha^{-1}. For the 2022/23 season, the XP739FP hybrid, which also tolerates ALS inhibitor herbicides, was used. It was sown on September 27, 2022, at a density of 45 kg ha^{-1}. For both seasons, the seeds were previously treated with thiamethoxam (0.88 g ai kg^{-1}), fludioxinil + metalaxyl-M (0.03 + 0.01 g ai kg^{-1}), gibberellic acid (0.007 g kg^{-1}), and zinc (1.8 g kg^{-1}).

Rice emergence occurred on October 11, 2021, and October 17, 2022, for the first and second crops, respectively. Weed management was carried out by applying glyphosate (1440 g ai ha^{-1} in the 2021/22 season and 1250 g ai ha^{-1} in the 2022/23 season) plus clomazone (360 g ai ha^{-1}) at the rice spiking stage (stage S3) on September 30, 2021, and October 5, 2022, for the first and second crops, respectively. Subsequently, the post-emergence application of florpyrauxifen-benzyl (23.9 g ai ha^{-1}) associated with cyhalofop-butyl (360 g ai ha^{-1}) was conducted at 25 and 26 days after crop emergence (DAE) for the first and second crops, respectively. The start of flooding irrigation occurred at 26 and 27 DAE for the first and second crops, respectively. Other cultural practices followed technical recommendations for rice cultivation.

The experimental treatments were arranged in a factorial design, in which factor A consisted of different times of pre-emergence herbicide application, denoted as "June," "July," and "August." Factor B was the application of the herbicides s-metolachlor (1440 g ai ha^{-1}), flumioxazin (50 g ai ha^{-1}), pyroxasulfone (170 g ai ha^{-1}), sulfentrazone + diuron (210 g and 420 g ai ha^{-1}, respectively), and the control (no herbicide). The times were named June, July, and August to facilitate the presentation of results, referring to applications made 100, 78, and 47 days before rice sowing, respectively, for the 2021/22 season and 42, 26, and 10 days before rice sowing, respectively, for the 2022/23 season. Treatment applications were carried out using a pressurized backpack sprayer with CO_2, equipped with 110,015 flat fan nozzles, at a spray volume of 150 L ha^{-1}. Application conditions for the 2021/22 season at 100, 78, and 47 days were as follows: air temperature 20, 22, and 23 ºC, respectively; relative humidity 76, 78, and 72%, respectively; and wind speed 3.8, 4.6, and 3.2 km h^{-1}, respectively. For the 2022/23 season at 42, 26, and 10 days, conditions were as follows: air temperature 26, 25, and 24 ºC, respectively; relative humidity 70, 72, and 74%, respectively; and wind speed 4.6, 4.8, and 3.4 km h^{-1}, respectively.

The variables assessed included the control (%) of weedy rice and crop injury (%) conducted at 36, 54, and 75 days after sowing (DAS), respectively, for the 2021/22 harvests and 33, 51, and 70 DAS for the 2022/23 harvests, respectively. Additionally, the control of weedy rice pre-harvest was evaluated using the percentage scale, in which 0 indicates no damage and 100 indicates plant death. Furthermore, the number of weedy rice plants was counted pre-harvest using metal frames with a known area of 0.25 m^2, with data presented in plants m^{-2}. The grain yield of the crop was also assessed, with a useful area of 25 m^2 harvested per plot, followed by subsequent threshing. Grain weight was measured, with yield expressed in kg ha^{-1}, with humidity corrected to 13%.

After harvest, the weedy rice seed bank was assessed by collecting soil samples using a 'mug' type auger (10 cm in diameter) at a depth of 0-10 cm (MACHADO et al., 2010). Ten collections (subsamples) were conducted in each plot. Following collection, the samples were washed to remove all soil, and the number of full and empty weedy rice seeds was counted. The full seeds were subjected to viability testing using the tetrazolium test (MAPA, 2009). To determine the number of seeds, this value was expressed per square meter by estimating the area of the cylinder (Equation 1) for data analysis.

$$A(m^2) = [2 \times \pi \times r(r + h)]/1000 \quad (1)$$

where A is the area in m^2, r is the radius of the cylinder diameter in cm, and h is the height of the cylinder in cm.

The data obtained underwent analysis of variance (ANOVA) ($P \leq 0.05$), followed by testing for ANOVA assumptions using the Shapiro-Wilk test ($P \geq 0.05$) to confirm the normal distribution of errors and the O'Neill-Matthews test ($P \geq 0.05$) to ensure the homogeneity of variances. In cases of significant differences, the Scott-Knott mean test ($P \leq 0.05$) was employed. For principal component analysis, the nomenclatures CDAE, WRP, FS, VS, and NS were used to represent the variables control (%), number of plants, and number of full, viable, and non-viable weedy rice seeds, respectively. The acronyms IDAE and YIELD denoted injury (%) and crop yield, respectively. Pearson's linear correlation coefficients were calculated for each data matrix of the 2021/2022 and 2022/2023 harvests between pairs of evaluated traits, with significance assessed using Student's t-test at a 5% level. Subsequently, a principal component analysis was conducted, stratified by herbicides and months of herbicide application. All analyses were performed using R software (R CORE TEAM, 2019).

For the 2021/2022 harvest, the data on control (%), injury (%), number of plants (WRP) of weedy rice per square meter pre-harvest, and the number of full, viable, and non-viable seeds of weedy rice per square meter did not meet the assumptions of the model. Similarly, for the 2022/2023 harvest, the data on control (%) and the number of full, viable, and non-viable seeds of weedy rice per square meter did not meet the assumptions of the model. Therefore, these data were transformed using the square root model: $y' = \sqrt{y+1}$, where y is the observed variable and y' is the variable after transformation.

RESULTS

Crop season 2021/2022

There was no interaction between the factors for the variables control (%) at 54 and 148 DAS, injury (%) at 54 and 75 DAS, yield (kg ha^{-1}), and number of full and non-viable seeds per square meter (m^{-2}) (Table 1). Analyzing the main effects of application timing showed that there were no significant differences for the control at 54 DAS and the number of non-viable seeds m^{-2}. Regarding the herbicide factor, there were no significant differences for the control variable at 148 DAS, yield, or number of full or non-viable seeds m^{-2} (Table 1). Efficiency in controlling weedy rice throughout the crop cycle with the use of pre-emergent herbicides was not observed when assessed at 54 and 148 DAS (Table 1). Injury values did not exceed 14% under any condition, indicating that flumioxazin and sulfentrazone + diuron caused greater damage to rice compared to other treatments at 75 DAS (Table 1). Grain yield did not significantly differ with the use of herbicides, except for the season factor, the lowest yield occurred in June, at 8576 kg ha^{-1}, which significantly differed from the others.

Regarding the number of filled seeds, a significant difference was observed for the season factor, with the highest seed density found in August at 75 filled seeds m^{-2} of soil. Furthermore, for the June, July, and August seasons, the number of non-viable seeds was 33, 24, and 47 seeds m^{-2} of soil, respectively. Concerning herbicides, the highest number of non-viable seeds was associated with the herbicide s-metolachlor, followed by sulfentrazone + diuron, with 35 and 28 seeds m^{-2} of soil, respectively. An interaction between the time of application and the herbicides used was observed for the variables of control at 36 and 75 DAS, injury at 36 DAS, number of weedy rice plants (WRP) m^{-2} pre-harvest (148 DAS), and viable seeds m^{-2} of soil (Table 2). The control provided by s-metolachlor and sulfentrazone + diuron was generally superior to the others, regardless of the application timing (Table 2). For these herbicides, the application had the greatest effect, approaching or reaching close to 10% for application in August and evaluation at 36 DAS. Overall, the application in August led to an increase in the control variable for all herbicides tested. However, applications in August resulted in greater injury to rice at 36 DAS, with rates of 14, 20, and 12% for herbicides s-metolachlor, sulfentrazone + diuron, and flumioxazin, respectively. The sulfentrazone + diuron herbicide differed from the non-application control in all seasons regarding the variable of injury at 36 DAS. However, the pyroxasulfone herbicide differed only from the control in terms of injury at this evaluation time in July, but its effect was inferior to the others (Table 2).

The highest number of weedy rice plants m^{-2} pre-harvest (148 DAS) was observed in June for the s-metolachlor herbicide, with 9 plants m^{-2} (Table 2). However, when the treatments were applied in August, the herbicides s-metolachlor and sulfentrazone + diuron differed from the other herbicides and the control, with no weedy rice plants

Table 1 - Control (%), number of full and non-viable seeds m^{-2} of weedy rice, injury (%), and rice crop yield according to the application timings and herbicides applied in off-season management. Dom Pedrito, RS, 2021/2022.

Application timings/ Herbicides	Control (%)		Injury (%)		Yield	Seeds m^{-2}	
	54 DAS[1]	148 DAS	54 DAS	75 DAS	(kg ha^{-1})	Full	Non-viable
---Application timings---							
June (Jun)	0 a[2]	0 b	4 b	7 b	8576 b	44 b	33 a
July (Jul)	0 a	0 b	4 b	6 b	10392 a	34 b	24 a
August (Aug)	0 a	1 a	8 a	12 a	9963 a	75 a	47 a
---Herbicides---							
Control	0 b	0 a	0 b	0 c	9845 a	46 a	33 a
S-metolachlor	1 a	0 a	7 a	9 b	9974 a	47 a	35 a
Sulfentrazone + diuron	1 a	1 a	8 a	12 a	9664 a	38 a	28 a
Pyroxasulfone	0 b	0 a	5 a	6 b	9754 a	89 a	59 a
Flumioxazin	0 b	0 a	7 a	14 a	8983 a	35 a	17 a
CV (%)	24.5	21.5	31.1	29.0	10.7	39.5	47.9

[1]Days after sowing.
[2]Averages followed by the same letter do not differ significantly by the Scott–Knot test at 5% probability.

Table 2 - Control (%), number of plants (WRP) m^{-2} pre-harvest, number of viable seeds m^{-2} of weedy rice, and crop injury (%) of rice according to the application timings and herbicides applied in off-season management. Dom Pedrito, RS, 2021/22.

Application timings Herbicides	Control (%)						Injury (%)			WRP		
	36 DAS[1]			75 DAS			36 DAS			148 DAS		
	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug
Control	0 Ba[2]	0 Ca	0 Ca	0 Aa	0 Aa	0 Ba	0 Da	0 Ca	0 Da	3 Ba	2 Aa	3 Aa
S-metolachlor	1 Bb	6 Aa	9 Aa	0 Ab	0 Ab	4 Aa	8 Bb	6 Ab	14 Ba	9 Aa	4 Ab	0 Bc
Sulfentrazone + diuron	5 Ab	8 Aa	10 Aa	0 Ab	0 Ab	5 Aa	15 Aa	8 Ab	20 Aa	1 Ba	1 Aa	0 Ba
Pyroxasulfone	0 Bb	1 Cb	4 Ba	0 Aa	0 Aa	1 Ba	5 Ca	3 Ba	6 Ca	1 Ba	1 Aa	2 Aa
Flumioxazin	0 Bb	3 Ba	5 Ba	0 Ab	0 Ab	3 Aa	10 Ba	7 Ab	12 Ba	1 Ba	2 Aa	2 Aa
CV (%)	25.3			20.9			15.2			27.3		

[1]Days after sowing.
[2]Capital letters compare treatments in the same timing (columns), and lowercase letters compare treatments between timings (rows). Averages followed by the same letter do not differ significantly by the Scott-Knot test at 5% probability.

observed in the area. Regarding the number of viable seeds in the soil, there was no difference between the herbicides in June or July (Table 3). However, in August, the highest values were observed for the pyroxasulfone and flumioxazin herbicides, with 58 and 43 viable seeds m^{-2} of soil, respectively. The lowest average values of viable seeds between the seasons were obtained with the s-metolachlor and sulfentrazone + diuron herbicides (12 and 11 seeds m^{-2} of soil, respectively).

The first two principal components explained 68.3% of the total variability in the data (Figure 1). The first principal component explained the greatest variation in the data; therefore, the horizontal distances between the observations or groups are more important than the vertical distances. The points or groups that are in the same direction as the variable vectors indicate higher expressions of these variables. Meanwhile, the points or groups located in opposite directions to the vectors indicate lower expressions of the variables. Distinct groups were formed when the biplot was stratified by the time of herbicide application. Herbicide application in July promoted greater control of weedy rice; although, this was associated with the occurrence of injury. However, applications in August promoted the highest numbers of full seeds (FS), viable seeds (VS), and non-viable seeds (NS). A significant positive correlation was found between yield (YIELD) and C30DAS (r = 0.50) (Figure 2), indicating that better weed control at 30 DAS contributed to improved rice yield performance. No significant correlations were

Table 3 - Number of viable seeds m^{-2} of weedy rice according to the application timings and herbicides applied in off-season management. Dom Pedrito, RS, 2021/22.

Application timings Herbicides	Viable seeds m^{-2}		
	June	July	August
Control	4 Aa[1]	15 Aa	19 Ba
S-metolachlor	10 Aa	21 Aa	6 Ba
Sulfentrazone + diuron	14 Aa	3 Aa	15 Ba
Pyroxasulfone	22 Ab	9 Ab	58 Aa
Flumioxazin	6 Ab	4 Ab	43 Aa
CV (%)	43.8		

[1]Capital letters compare treatments within the same timing (columns), while lowercase letters compare treatments across timings (rows). Means followed by the same letter do not differ significantly according to the Scott-Knott test at 5% probability.

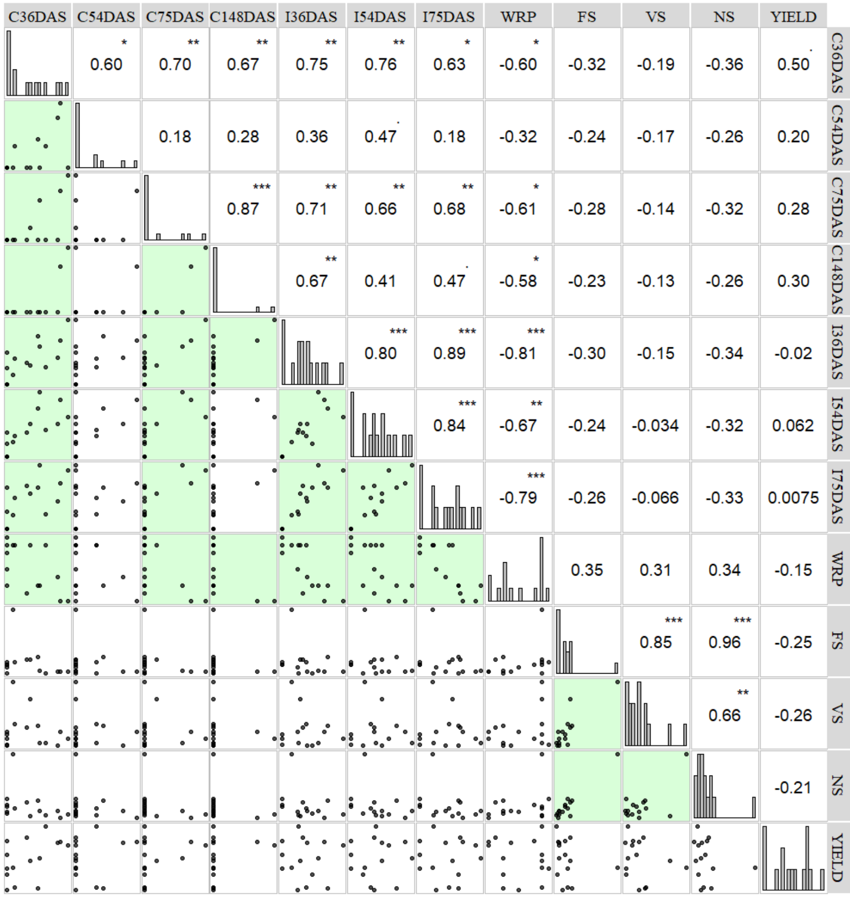

Figure 1 - Total data variability represented by two main components stratified by the time of application and herbicides applied in the off-season. Dom Pedrito, RS, 2021/2022.

*Characters: control (%) at 36 (C36DAS), 54 (C54DAS), 75 (C75DAS), and 148 (C148DAS) days after sowing (DAS); number of plants m^{-2} (WRP); number of full (FS), viable (VS), and non-viable (NS) seeds m^{-2} of weedy rice; injury (%) at 36 (I36DAS), 54 (I54DAS), and 75 (I75DAS) days after sowing (DAS) and crop grain yield (YIELD, kg ha^{-1}).

observed between injury and YIELD, suggesting that although injury was observed, it did not influence rice yield. The greatest control of weedy rice at 36, 54, 75, and 148 DAS was associated with the greatest injury at 36, 54, and 75 DAS. Negative coefficients were observed between C36DAS, C54DAS, C76DAS, C148DAS, I36DAS, I54DAS, and I75DAS with WRP, indicating that higher levels of control and injury led to lower levels of WRP.

Crop season 2022/2023

According to ANOVA, there was no interaction between the factors for the control variables (%) at 51 and 146 DAS, injury (%) at 51 and 70 DAS, number of plants m^{-2} of weedy rice (WRP) in rice pre-harvest, and crop grain yield (kg ha^{-1}), with only the simple effect of each factor being analyzed (Table 4). For the time application factor, the best control performance occurred in the third application time (August), but with values below 2%. Concerning the herbicide factor, the best performances in the rice pre-harvest evaluation were observed with s-metolachlor and sulfentrazone + diuron, with 2 and 3%, respectively. Similarly, the highest levels of injury to the crop occurred during the application carried out in August, reaching 13%, which differed from other times. For herbicides, the highest values were recorded for s-metolachlor, sulfentrazone + diuron, and flumioxazin at both evaluation times (51 and 70 DAS) (refer to Table 4).

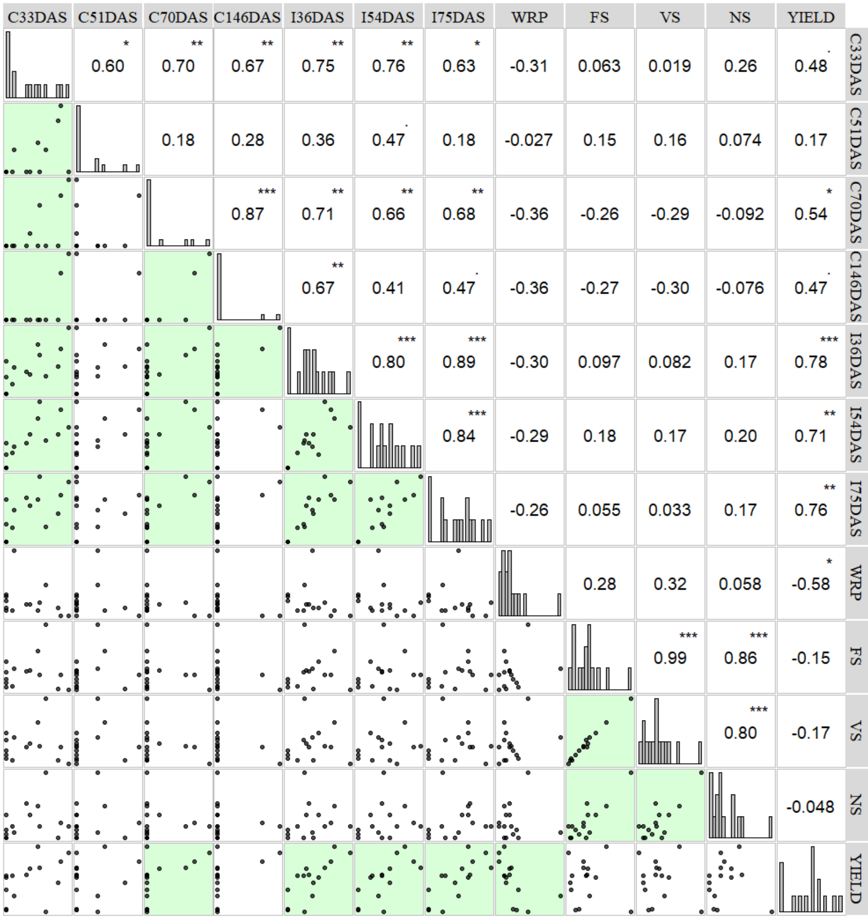

Figure 2 - Pearson's linear correlation coefficients between pairs of characters in the 2021/2022 harvest.

*Characters: control (%) at 36 (C36DAS), 54 (C54DAS), 75 (C75DAS), and 148 (C148DAS) days after sowing (DAS); number of plants m^{-2} (WRP); number of full (FS), viable (VS), and non-viable (NS) seeds m^{-2} of weedy rice; injury (%) at 36 (I36DAS), 54 (I54DAS), and 75 (I75DAS) days after sowing (DAS), and crop grain yield (YIELD, kg ha^{-1}). **, *** significant at 5, 1, and 0.01% by Student's t-test.

For the variable number of weedy rice plants m^{-2} pre-harvest, no difference was observed between the application times. However, the treatment without herbicide application (control) exhibited the highest number of plants, at 6 m^{-2}, which was at least three times higher than the average of the treatments with herbicide application. Despite a difference in yield of nearly 300 kg ha^{-1}, there was no significant distinction between the time applications. Nevertheless, treatments utilizing s-metolachlor and sulfentrazone + diuron achieved an average increase of 9% (735 kg ha^{-1}) compared to the control (Table 4). When analyzing the percentage of control at 33 and 70 days after sowing (DAS) and injury at 33 DAS, a significant interaction between the factors was observed (Table 5). The highest control values were achieved in August for all herbicides in both evaluations (33 and 70 DAS). Herbicides, such as s-metolachlor and sulfentrazone + diuron, exhibited the best performance regardless of the application timing, reaching peak values during the August application, with 24 and 14%, respectively, at 33 DAS (Table 5). Regarding injury values, the herbicides s-metolachlor, sulfentrazone + diuron, and flumioxazin exhibited injury values greater than 10% at all application times. This effect was most pronounced in August, in which values approached or exceeded 30%, differing significantly from other

Table 4 - Control (%), number of weedy rice plants (WRP) m^{-2} at pre-harvest of the crop, crop injury (%), and rice crop yield according to the application timings and herbicides applied in off-season management. Dom Pedrito, RS, 2022/23.

Application timings Herbicides	Control (%)		Injury (%)		WRP	Yield
	51 DAS[1]	146 DAS	51 DAS	70 DAS	146 DAS	(kg ha^{-1})
Application timings						
June	1 b[2]	0 b	6 b	10 b	3 a	8236 a
July	2 b	1 b	7 b	11 b	2 a	7927 a
August	4 a	2 a	13 a	14 a	2 a	7961 a
Herbicides						
Control	0 c	0 b	0 d	0 c	6 a	7587 c
S-metolachlor	7 a	3 a	11 b	15 a	2 b	8394 a
Sulfentrazone + diuron	5 b	2 a	15 a	18 a	1 b	8250 a
Pyroxasulfone	1 c	1 b	5 c	7 b	2 b	7937 b
Flumioxazin	0 c	0 b	11 b	18 a	2 b	8039 b
CV (%)	26.2	42.7	43.4	36.5	50.2	5.9

[1]Days after sowing.
[2]Means followed by the same letter do not differ significantly according to the Scott-Knott test at 5% probability.

treatments. Conversely, pyroxasulfone demonstrated injury values lower than 8%, indicating a higher level of selectivity for the crop at the tested dosage (Table 5).

For assessments of the number of full and viable seeds m^{-2} of soil, there was no interaction between the factors, with only the simple effect analyzed. Regarding the application times, there was no significant difference observed for full or viable seeds. Regarding herbicides, the treatments that exhibited the highest values of full seeds were flumioxazin and s-metolachlor, with 27 and 20 full seeds m^{-2} of soil, respectively. Similarly, these treatments showed the highest number of viable seeds (Table 6). For the number of non-viable seeds m^{-2} of soil, an interaction between the factors was observed. The standout performer was the herbicide flumioxazin, which significantly differed from the others in June, with 9 non-viable seeds m^{-2} of soil. In general, the average number of non-viable seeds was higher in August (Table 7).

The first two principal components explained 71.4% of the total data variability (Figure 3). Distinct groups were formed when the biplot

Table 5 - Control (%) of weedy rice and crop injury (%) of rice crops according to the application timings and herbicides applied in off-season management. Dom Pedrito, RS, 2022/23.

Application timings Herbicides	Control (%)						Injury (%)		
	33 DAS[1]			70 DAS			33 DAS		
	June	July	August	June	July	August	June	July	August
Control	0 Ba[2]	0 Ba	0 Da	0 Aa	0 Ba	0 Ba	0 Ba	0 Ca	0 Da
S-metolachlor	4 Ac	9 Ab	24 Aa	2 Ac	5 Ab	9 Aa	11 Ab	14 Ab	29 Ba
Sulfentrazone + diuron	3 Ac	6 Ab	14 Ba	0 Ab	0 Bb	6 Aa	15 Ab	15 Ab	34 Aa
Piroxasulfone	0 Bb	3 Ba	5 Ca	0 Aa	0 Ba	1 Ba	4 Ba	6 Ba	8 Ca
Flumioxazin	0 Bb	3 Ba	5 Ca	0 Ab	0 Bb	3 Ba	10 Ab	13 Ab	35 Aa
CV (%)	29.5			31.7			28.9		

[1]Days after sowing.
[2]Capital letters compare treatments within the same timing (columns), and lowercase letters compare treatments across timings (rows). Means followed by the same letter do not differ significantly according to the Scott-Knott test at 5% probability.

Table 6 - Number of full and viable seeds m^{-2} according to the application timings and herbicides applied in off-season management. Dom Pedrito, RS, 2022/23.

Application timings Herbicides	---------Number of seeds m^{-2}--------	
	-------Full-------	-----Viable------
------------------------Application timings------------------------		
June	19 a[1]	17 a
July	14 a	13 a
August	16 a	13 a
-------------------------------Herbicides----------------------------		
Control	9 b	7 b
S-metolachlor	20 a	17 a
Sulfentrazone + diuron	12 b	11 b
Pyroxasulfone	13 b	11 b
Flumioxazin	27 a	24 a
CV (%)	------49.0-------	------49.0-------

[1]Means followed by the same letter do not differ significantly according to the Scott-Knott test at 5% probability.

was stratified by herbicide application times. It was observed that the application of herbicides in July promoted the greatest control of weedy rice, albeit associated with the occurrence of injury. However, the response patterns were not identifiable when the biplot was stratified by herbicides. A significant positive correlation was found between YIELD and C33DAS, C70DAS, and C146DAS (r = 0.48, r = 0.54, and r = 0.47, respectively) (Figure 4). This indicated that greater control of weedy rice at 33, 70, and 146 DAS promotes better crop yield performance. Significant correlations of YIELD with I33DAS, I51DAS, and I70DAS were also observed. This suggested that; although, injury occurred in the crop, the control of weedy rice promoted better rice yield performance. Thus, it can be inferred that the damage caused by injury, as observed in the present study, does not necessarily imply a reduction in yield. The greater control of weedy rice at 33, 51, 70, and 146 DAS was associated with greater injury at 33, 51, and 70 DAS. Negative coefficients were observed between C33DAS, C51DAS, C70DAS, C146DAS, I33DAS, I51DAS, and I70DAS with WRP. Therefore, it can be inferred that the greater the control and injury, the lower the presence of weedy rice plants (WRP).

DISCUSSION

In general, across both harvests, herbicides showed inefficiency in controlling weedy rice, as values below 39% are considered ineffective (SBCPD, 1995), despite significant differences. This conclusion is supported by the absence of control greater than 3% observed in the pre-harvest of rice (148 and 146 DAS, for the first and second harvest). Consistent with the findings of this study, chemical management employing s-metolachlor (1440 g ai ha^{-1}) was ineffective in controlling weedy rice when applied 73 and 43 days before sowing the crop in Santa Catarina State, Brazil (OLIVEIRA NETO et al., 2020). However, herbicides, such as s-metolachlor and sulfentrazone + diuron, provided better control results than the others. Additionally, application in August appeared to enhance the effectiveness of herbicides compared to other times. Furthermore, when comparing the results between the two harvests, an increase of 15% and 4% in the control of weedy rice was observed during the first evaluation period for the herbicides s-metolachlor and sulfentrazone + diuron, respectively, in the 2022/2023 harvest. This response can be attributed to the shorter interval between the application and sowing of the crop during this time in different harvests, which was 47 and 10 days for 2021/2022 and 2022/2023, respectively.

The pyroxasulfone herbicide has the same mechanism of action as s-metolachlor, although they come from different chemical groups (HRAC, 2022). Despite demonstrating satisfactory control of monocotyledonous species (KHALIL et al., 2019), its performance in controlling weedy rice was not as promising as s-metolachlor, reaching maximum values of 5%, similar to the herbicide flumioxazin. In soybean cultivation, the pre-emergence use (4 and 11 days before sowing) of pyroxasulfone (89 g ai

Table 7 - Number of non-viable seeds m^{-2} according to the application timings and herbicides applied in off-season management. Dom Pedrito, RS, 2022/23.

Application timings Herbicides	--Number of non-viable seeds m^{-2}--		
	June	July	August
Control	0 Ba[1]	2 Aa	1 Aa
S-metolachlor	1 Ba	4 Aa	3 Aa
Sulfentrazone + diuron	1 Ba	0 Aa	3 Aa
Piroxasulfone	1 Ba	1 Aa	4 Aa
Flumioxazin	9 Aa	0 Ab	1 Ab
CV (%)	-------------------46.9-------------------		

[1]Capital letters compare treatments within the same timing (columns), and lowercase letters compare treatments across timings (rows). Means followed by the same letter do not differ significantly according to the Scott-Knott test at 5% probability.

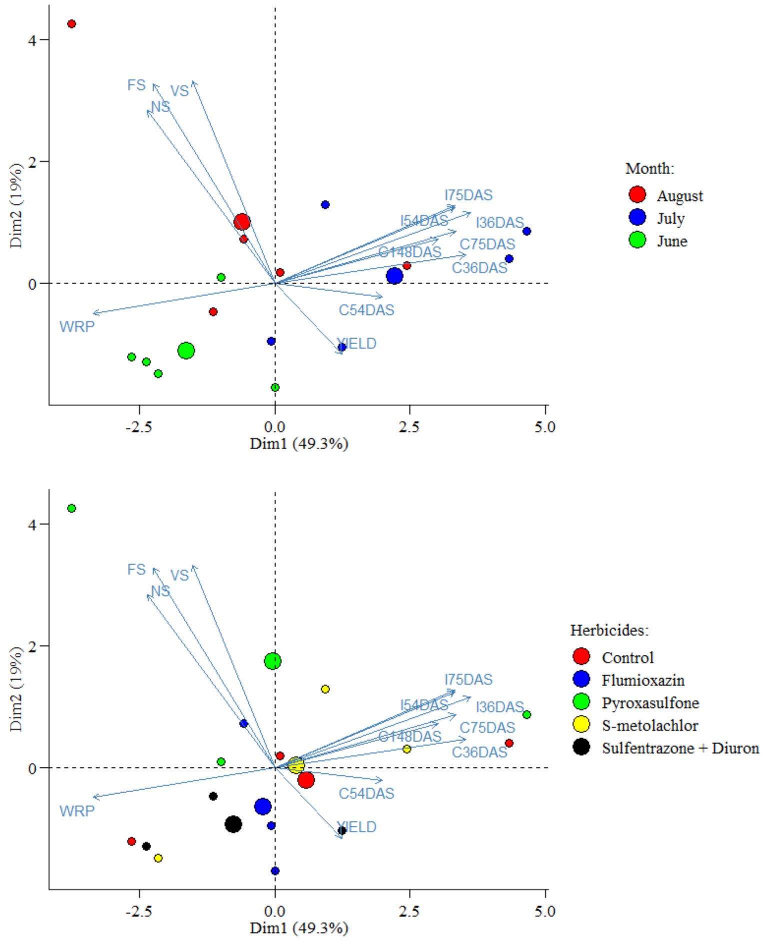

Figure 3 - Total data variability represented by two main components stratified by the time of application and herbicides applied in the off-season. Dom Pedrito, RS, 2022/2023.

*Characters: control (%) at 33 (C33DAS), 51 (C51DAS), 70 (C70DAS), and 146 (C146DAS) days after sowing (DAS); number of plants m^{-2} (WRP); number of full (FS), viable (VS), and non-viable (NS) seeds m^{-2} of weedy rice; injury (%) at 33 (I33DAS), 51 (I51DAS), and 70 (I70DAS) days after sowing (DAS), and crop grain yield (YIELD, kg ha^{-1}).

ha^{-1}) provides satisfactory control of several weeds without causing injury to the crop (MAHONEY et al., 2014), making it recommended for controlling weedy rice. In this scenario, it is possible to apply after sowing (plant-apply), allowing for effective residual action in the establishment of the soybean crop, thereby reducing losses due to competition with weeds. Promising results were observed in the United States with the application of pre-emergent herbicides 192 days before sowing, coupled with flooding of the area before rice sowing, using s-metolachlor (1070 g ai ha^{-1}) and pyroxasulfone (205 g ai ha^{-1}), which achieved efficiencies of 84 and 82%, respectively (BERTUCCI et al., 2019). However, when the dose of pyroxasulfone was increased to 410 g ai ha^{-1}, there was 20% injury in the crop (BERTUCCI et al., 2019). In addition to the responses of the cultivars themselves, injury to the crop varies depending on the doses used and the timing of herbicide application (BERTUCCI et al., 2019; SHRESTHA et al., 2019; MAHAJAN & CHAUHAN, 2022).

Considering that these herbicides are not selective to rice, applications were conducted early to mitigate yield losses. Similar trends were observed for other tested herbicides, such as flumioxazin, which exhibited low control efficiency in all evaluations

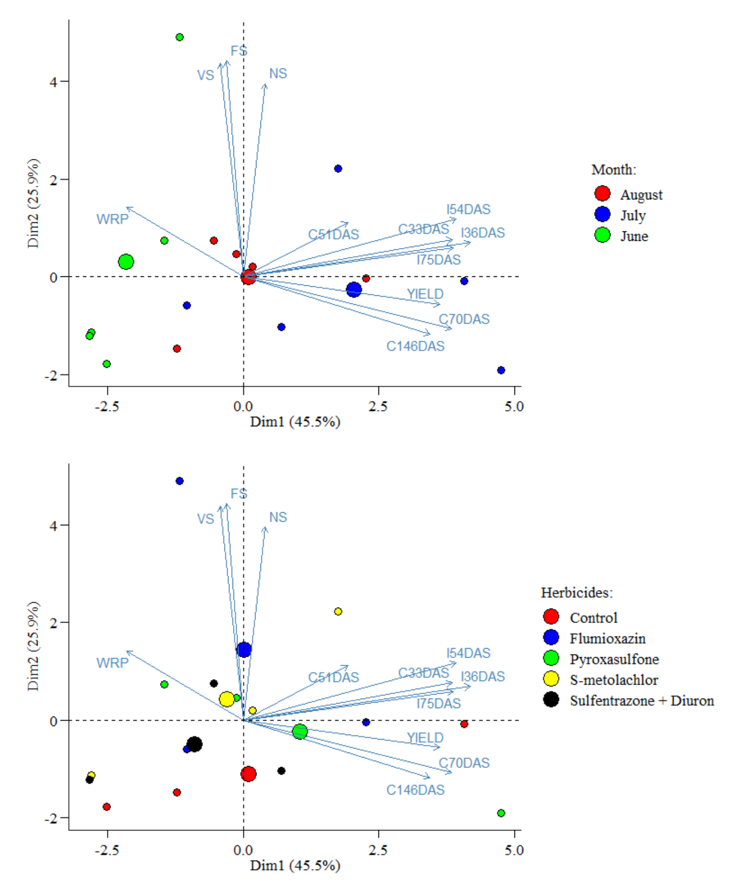

Figure 4 - Pearson's linear correlation coefficients between pairs of characters in the 2022/2023 harvest.

*Characters: control (%) at 33 (C33DAS), 51 (C51DAS), 70 (C70DAS), and 146 (C146DAS) days after sowing (DAS); number of plants m^{-2} (WRP); number of full (FS), viable (VS), and non-viable (NS) seeds m^{-2} of weedy rice; injury (%) at 33 (I33DAS), 51 (I51DAS), and 70 (I70DAS) days after sowing (DAS), and crop grain yield (YIELD, kg ha^{-1}). *, **, *** significant at 5, 1, and 0.01% by Student's t-test.

and did not differ significantly from the control. In a study evaluating the response of 54 weedy rice biotypes to select herbicide tolerance traits, the herbicide flumioxazin (72 g ai ha^{-1}), when applied to pre-germinated seeds before planting, caused injury above 80% for 48 of the biotypes tested, justifying a 30-day application interval for the region under study (SHRESTHA et al., 2019). Another factor contributing to the low control values obtained is the dormancy of the weedy rice seeds. The seeds remain dormant, and their emergence occurs when environmental conditions become conducive to overcoming this dormancy (AGOSTINETTO et al., 2001; NADIR et al., 2017). Emergence of weedy rice is favored during months with higher air and soil temperatures, such as November and December (SARTORI et al., 2014). Therefore, considering that herbicide applications were carried out between June and September, there was no residual herbicide during the period of the greatest weed emergence.

As noted, the primary challenge in controlling weedy rice stems from its close relation to cultivated rice. Consequently, herbicides that exhibited greater visual control of the weed tended to induce more significant injury effects on the crop. In the 2022/2023 harvest, due to shorter intervals between application and sowing, influenced by prevailing climatic conditions (< 42 days), the highest levels of injury were observed. Thus, it is crucial to emphasize that applying the tested herbicides at intervals typically shorter than 26 days may not ensure low levels of injury. In the shortest interval between application and sowing (10 days), the injury values were 35, 34, and 29% for flumioxazin, sulfentrazone + diuron, and s-metolachlor, respectively, in the first evaluation (33 DAS). However, when applied at intervals of 26 days before sowing, these herbicides reached average values of 13, 18, and 14%, respectively. The herbicides flumioxazin (60 g ai ha^{-1}) and s-metolachlor (1400 g ai ha^{-1}) can cause up to 100% mortality in rice plants when applied close to or shortly after sowing (plant-apply) (MAHAJAN & CHAUHAN, 2022); and therefore, are not recommended in this situation. Despite this, a study lasting six years and utilizing two application doses evaluated autumn management of ryegrass (*Lolium perene* ssp. *multiflorum* (Lam.) Husn) with applications six months before rice sowing and reported crop damage values at 14 DAS of 30 and 37% for s-metolachlor (1420 and 2840 g ai ha^{-1}) and pyroxasulfone (170 and 340 g ai ha^{-1}), respectively, without causing yield losses (LAWRENCE et al., 2018).

Experiments verified the selectivity of herbicides to wheat (*Triticum aestivum* L.), and used of sulfentrazone + diuron (175 + 350 g ai ha^{-1}) pre-emergence (plant-apply) showing the highest crop yield, despite of an injury of 46% (GALON et al., 2021). Similarly, a study with rice in the seedling transplantation cultivation system evaluated the use of sulfentrazone at a dose of 96 g ai ha^{-1} applied three days before transplantation. No injury was observed in the crop; however, there was a 50% increase in yield (BHUIYAN et al., 2017), which can be attributed to the reduced competition with weeds in treatments with herbicide application. These findings support those found in the literature regarding the effects of injury on crops, in which grain yield was not significantly affected due to the damage caused by herbicides.

For the application time factor, during the 2021/22 harvest, the lowest yield was observed in June at 8576 kg ha^{-1}, followed by August (10,392 kg ha^{-1}) and July (9963 kg ha^{-1}), with no statistically significant difference between them. This could be attributed to the presence of weedy rice plants in the pre-harvest crop, particularly 3 plants m^{-2} in the first time. Consequently, throughout the cultivation cycle, there was competition between the weeds and the crop, likely due to the longer interval between herbicide application and sowing. In August, treatments with s-metolachlor and sulfentrazone + diuron differed from the other herbicides and controls, displaying no weedy rice plants in the area. In the 2022/23 harvest, the treatment without herbicide application exhibited a 10.4% reduction in yield compared to the treatment with a higher yield (s-metolachlor). This decline is attributable to increased competition between the crop and the weeds, as no herbicide was applied in this treatment. Consequently, the population of weedy rice was 6 plants m^{-2} in the pre-harvest rice, competing with the crop throughout the cultivation cycle.

Regarding the seed bank in the soil, in the initial harvest, there was a higher number of full seeds, with over 50% (of the total number of full seeds m^{-2}) being unviable. Specifically, there were 33, 24, and 47 seeds m^{-2} of soil for June, July, and August, respectively. The highest values of non-viable seeds were associated with s-metolachlor and sulfentrazone + diuron, with 35 and 28 seeds m^{-2} of soil, respectively. In the subsequent 2022/23 harvest, there were fewer full seeds for both seasons and herbicides. However, there was a higher number of viable seeds out of the total seeds m^{-2} of the soil. Moreover, there was an increased number of unviable seeds in August, with 12 seeds m^{-2} of soil. In this context, it is plausible that herbicides were effective in the seed bank, as the use of pre-emergent herbicides can maintain or even reduce seed bank density (RAHMAN et al., 2001; AIMIM et al., 2016).

Despite the low control values, it is essential to highlight the impact on the reduction in the number of weedy rice plants per area, which was particularly evident in the 2022/23 harvest. Moreover, the decrease in the number of weedy rice plants results in a reduction in the seed source entering the soil, which is the primary mechanism for maintaining the species in the seed bank (RADOSEVICH et al., 2007). Consequently, the use of pre-emergence herbicides appears to contribute to diminishing the seed bank over successive harvests (AIMIM et al., 2016). This action serves as a supplementary tool to other management practices, such as crop rotation, utilization of herbicide-tolerant rice cultivars, and sowing at optimal times. Nevertheless, further studies are warranted to confirm and establish the potential use of this approach in irrigated rice areas.

CONCLUSION

The use of herbicides s-metolachlor (1440 g ai ha^{-1}), sulfentrazone + diuron (210 + 420 g ai ha^{-1}), pyroxasulfone (170 g ai ha^{-1}), and flumioxazin (50 g ai ha^{-1}) applied before rice sowing did not control more than 24% of weedy rice in rice crops. The herbicides s-metolachlor (1440 g ai ha^{-1}) and sulfentrazone + diuron (210 + 420 g ai ha^{-1}) when applied at intervals of up to 26 days before sowing the crop caused low injury without significantly affecting crop yield. The herbicide pyroxasulfone (170 g ai ha^{-1}) did not present injury to the crop when applied at intervals of up to 10 days before rice sowing.

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DECLARATION OF CONFLICT OF INTEREST

We have no conflict of interest to declare.

AUTHORS' CONTRIBUITIONS

The authors contributed equally to the setup, data collection, and analysis, as well as the writing of the manuscript.

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