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Full Length Article

Control of Poaceae and Convolvulaceae Weed Species by Herbicides Applied to the Soil and Sugarcane Straw

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Abstract

Ban on burning of sugarcane plant residues and partial or full straw removal, as well as its heterogeneous distribution in a field, affect the weed flora and dynamics of herbicides applied as pre-emergence. This study aimed to evaluate whether pre-emergence herbicides applied directly to the soil or onto different sugarcane straw amounts could efficiently control *Urochloa decumbens*, *Digitaria horizontalis*, *Cenchrus echinatus*, *Ipomoea triloba* and *Merremia aegyptia*. A greenhouse experiment was carried out in a fully randomized design arranged in a 12 × 5 factorial scheme (factors A and B). Factor A consisted of 12 treatments: (isoxaflutole, clomazone, sulfentrazone, indaziflam, amicarbazone, tebuthiuron, s-metolachlor + [diuron + hexazinone], imazapic, amicarbazone + tebuthiuron, indaziflam + metribuzin, and [indaziflam + isoxaflutole] and control without herbicide. Factor B comprised of five amounts of sugarcane straw (0, 2, 6, 8 and 10 t ha^{-1}). When applied directly to the soil or on sugarcane straw, s-metolachlor + [diuron + hexazinone] and indaziflam + metribuzin satisfactorily controlled *C. echinatus*, *U. decumbens*, and *D. horizontalis*. Sulfentrazone, amicarbazone + tebuthiuron and indaziflam + isoxaflutole were efficient in controlling *C. echinatus* and *U. decumbens*, but not *D. horizontalis* regardless of the straw presence. Under the same conditions, sulfentrazone, tebuthiuron and amicarbazone + tebuthiuron satisfactorily controlled *I. triloba* and *M. aegyptia*. Amicarbazone and imazapic were efficient in controlling *I. triloba* only when applied on sugarcane straw. Except for imazapic, *M. aegyptia* was susceptible to all herbicides used and application conditions. Species from the same family may have similar susceptibility although there may be some exceptions. The highly water-soluble herbicides tested in this study showed satisfactory control efficiency even on high amounts of straw. © 2022 Friends Science Publishers

Keywords: Chemical control; Grasses; Green cane; Morning glory; Pre-emergence

Introduction

Brazil is the largest sugarcane producer worldwide (FAO 2021), with an estimated production of 628.1 million tons over an area of about 8.42 million hectares in the 2021/2022 crop season (CONAB 2021). However, changes in legislation to protect environment have affected sugarcane production systems during the last two decades (Kuva *et al.* 2013). (*e.g.*, see: state of São Paulo Art. n° 1 of the Law No. 11,241 of September 19, 2002; Paulo 2002). Prohibiting sugarcane burning generated a production system known as "green cane," in which straw remains on the soil surface, thus affecting weed flora (Kuva *et al.* 2013) and herbicide dynamics in the soil as a function of its physicochemical properties (Christoffoleti and López-Ovejero 2005; Monquero *et al.* 2007; Silva and Monquero 2013; Carbonari *et al.* 2016).

Weed interference can adversely affect sugarcane production. Stalk yield reductions of 33% have been reported in areas with predominance of *Panicum maximum*, *Acanthospermum hispidum*, and *Alternanthera tenella* (Meirelles *et al.* 2009). A sugarcane yield reduction of 40% has been observed in areas infested by *U. decumbens* and *P. maximum* (Kuva *et al.* 2003). In sugarcane fields infested with *I. hederifolia*, yield reductions can reach to 46% (Silva *et al.* 2009). The absence of weed control measures in sugarcane fields during the critical period of interference prevention - CPIP (between 20 and 150 days after planting) may generate yield losses of up to 85% (Filho and Christoffoleti 2004). The CPIP is a period when weed control measures are important to avoid continuing interference of weeds with crops (Kozlowski 2002).

Weed control strategies are essential to increase sugarcane yields. Among the most used, chemical methods stand out (Kuva and Salgado 2014). Chemical control, both as pre- and post-emergence, has been the most used in sugarcane fields because of its greater effectiveness, practicality, and low costs (Santos and Borém 2016).

In green cane production systems, straw composition and amounts may change, influencing weed initial emergence and altering pre-emergence herbicide dynamics when applied on straw (Rossi *et al.* 2013). As straw exerts a physical barrier, herbicides must have specific physicochemical characteristics such as: low octanol-water partition coefficient (Kow), high water solubility, and low vapor pressure (Christoffoleti *et al.* 2008; Silva and Monquero 2013).

Weed species such as *Urochloa decumbens*, *Digitaria horizontalis*, *Cenchrus echinatus*, *Ipomoea triloba* and *Merremia aegyptia* are predominant in sugarcane fields with heterogeneous distribution or total removal of straw (Kuva *et al.* 2013; Silva *et al.* 2018). In this context, testing the effectiveness of herbicides commonly used in mechanized sugarcane farming is relevant for management of difficult-to-control weeds in the presence of straw (Ferreira *et al.* 2020).

Based on the above scenario, this study tested whether herbicides of different solubility levels (amicarbazone, clomazone, imazapic, indaziflam, isoxaflutole, sulfentrazone, tebuthiuron, amicarbazone + tebuthiuron, s-metolachlor + [diuron + hexazinone], [indaziflam + isoxaflutole] and indaziflam + metribuzin) applied to soil or on different sugarcane straw amounts (2, 6, 8 and 10 t ha^{-1}) may promote satisfactory control, reducing dry mass of the various weed species *Urochloa decumbens*, *Digitaria horizontalis*, *Cenchrus echinatus*, *Ipomoea triloba* and *Merremia aegyptia*.

Materials and Methods

Facilities and experimental design

Weed control experiments were carried out in a greenhouse at the Center for Agricultural Sciences, Federal University of São Carlos, Araras-SP, Brazil (22°18'57.3"S 47°23'24.2"W). The area has a *Cwa* type climate, which stands for hot and humid summers and dry winters (Köppen 1948).

The experiment was carried out in a fully randomized design and arranged in a 12 × 5 factorial scheme (factors A and B), with four replications for each weed species. Five weed species were studied, namely *Cenchrus echinatus* (CCHEC, southern sandbur, Poaceae family), *Digitaria horizontalis* (DIGHO, Jamaican crabgrass, Poaceae family), *Ipomoea triloba* (IPOTR, morning glory, Convolvulaceae family), *Merremia aegyptia* (IPOPE, morning glory, Convolvulaceae family), and *Urochloa decumbens* (BRADC, brachiaria, Poaceae family).

The first factor (A) consisted of 12 treatments, among which there was a control (without herbicide spraying) and 11 treatments were herbicides: amicarbazone (1050 g ai ha^{-1}), clomazone (900 g ai ha^{-1}), imazapic (245 g ai ha^{-1}), indaziflam (75 g ai ha^{-1}), isoxaflutole (150 g ai ha^{-1}), sulfentrazone (800 g ai ha^{-1}), tebuthiuron (1000 g ai ha^{-1}), amicarbazone + tebuthiuron (1050 + 750 g ai ha^{-1}), s-metolachlor + [diuron + hexazinone] (1680 + 1500 g ai ha^{-1}), [indaziflam + isoxaflutole] (45 + 135 g ai ha^{-1}), and indaziflam + metribuzin (95 + 1125 g ai ha^{-1}).

The second factor (B) comprised five different amounts of sugarcane straw simulated, which were equivalent to 0, 2, 6, 8 and 10 t ha^{-1}. Sugarcane straw was collected from sugarcane fields without history of recent herbicide application. The amounts of straw were dried outdoors, manually chopped with scissors, and then stored in a dry place until the beginning of the experiment. The amount of straw to be distributed over the surface of experimental units was calculated considering the area and simulated amounts.

The experimental units comprised 5-L plastic pots filled with crushed and sieved soil from topsoil (0–20 cm depth) of a farmland. The soil was classified as a dystroferric Red Latosol according to the Brazilian soil classification system - SiBCS (Yoshida and Stolf 2016), with low fertility and high iron contents. Its chemical properties are as follows:

P (resin) = 12 mg dm^{-3}, organic matter = 37 g dm^{-3}, pH ($CaCl_2$) = 5.4, K^+ = 3.7 mmolc dm^{-3}, Ca^{2+} = 68 mmolc dm^{-3}, Mg^{2+} = 10 mmolc dm^{-3}, H+Al = 26 mmolc dm^{-3}, SB = 81.7 mmolc dm^{-3}, CEC = 107.7 mmolc dm^{-3} and V = 76%.

For all weed species, 15 seeds per pot were sown at 1 cm depth. All the weed species had an average germination of 70%. Therefore, 10 plants were kept per pot throughout the experiment, considering the control as well. After sowing, the pots were irrigated to a 5 mm depth, and different amounts of sugarcane straw were placed onto the surface of each pot.

Herbicides were sprayed on different days, with applications lasting 30 min. Application conditions were measured using a Kestrel 3000 meteorological station. Measurements were 82.4°F ± 35.06°C temperature, 67.5 ±5.2% relative humidity, and 1.36 MPH application speed. Applications were performed using a costal CO_2-pressurized knapsack sprayer at a 2.1 Kgf cm^{-2} constant pressure. The sprayer was equipped with a 1.5-m long spray bar containing four Teejet XR 110.02 flat-fan nozzles, spaced 0.5 m apart, and calibrated to deliver 200 L ha^{-1} spray solution.

After spraying, the pots were relocated within the greenhouse space to simulate a 20-mm water depth, aiming to overlap the herbicides on the different straw amounts. After one day, the straw amounts were carefully removed from the pots, which remained in the same environment under daily automatic irrigation *via* micro-sprinkler, to meet phenological demands until the end of the experiment.

Experimental evaluations

The sample units were evaluated up to 35 days after emergence (DAE) of plants in control treatment (standard emergence). Weed control effectiveness was assessed by a visual scale developed by the *Asociación Latinoamericana De Malezas*, which is a score percentage scale; wherein: 0

corresponds to no weed control and 100% to death of all weed plants (ALAM 1974). Plant dry mass was measured at 35 DAE by cutting plants at ground level and placing the samples in paper bags, which were taken to a forced air circulation oven at 60ºC until dried and reached constant weight. The samples were measured with the aid of an analytical scale.

Shoot dry mass reduction (SDMR) was determined according to the following formula:

$$SDMR\ (\%) = \left[1 - \left(\frac{SDMt}{SDMc}\right)\right] \times 100$$

Wherein: *SDMR* (%) is the percentage of shoot dry mass reduction in the treatment, *SDMt* is the average shoot dry mass of the treatment and *SDMc* is the average shoot dry mass of the control.

Statistical analysis

The data on weed control efficiency and dry mass were tested for normality and homogeneity before the analysis of variance (ANOVA) and Scott-Knott mean comparison test ($P<0.05$). When interaction proved to be non-significant, a statistical breakdown was performed. Because of uncontrolled factors, assumptions of data normality were not met by the Shapiro-Wilk test. Therefore, original data were transformed by arcsine (root[x/100]) to meet basic ANOVA hypothesis (analysis of variances); however, the data shown in result tables are the original ones (Little and Hills 1972).

Results

For *Cenchrus echinatus*, there was an interaction between factors (herbicide and straw amounts) for visual control (%) and for SDMR according to the statistical breakdown (Table 1). The treatments amicarbazone + tebuthiuron, [indaziflam + isoxaflutole], s-metolachlor + [diuron + hexazinone], imazapic and indaziflam + metribuzin reduced effectively shoot dry mass (SDM) reduction of *C. echinatus*, regardless of the straw amount and conditions studied (Table 1). Amicarbazone, sulfentrazone, and tebuthiuron had no satisfactory control of *C. echinatus* in pots with 2 and 6 t ha^{-1} straw, with SDMR values below 68 and 46%, respectively.

For the application on 8 t ha^{-1} straw, sulfentrazone, clomazone, isoxaflutole, and tebuthiuron had similar control efficiencies (below 86%), whereas amicarbazone controlled about 44%. On 10 t ha^{-1} straw, amicarbazone + tebuthiuron, [indaziflam + isoxaflutole], s-metolachlor + [diuron + hexazinone], imazapic, indaziflam + metribuzin, isoxaflutole and clomazone reached the highest control efficiency (above 88%), while the others controlled on average less than 79% and were similar among them.

Regarding the control +of *C. echinatus*, SDMR values in pots with 8 and 10 t ha^{-1} straw were higher for isoxaflutole, amicarbazone + tebuthiuron, imazapic, s-metolachlor + [diuron + hexazinone], indaziflam + metribuzin, [indaziflam + isoxaflutole] and indaziflam. These herbicides were statistically equal and had control efficiencies above 91%. Amicarbazone and tebuthiuron promoted 67% reductions in SDMR of *C. echinatus* when applied on 6, 8 and 10 t ha^{-1} straw. Regardless of the straw amount, sulfentrazone promoted a low SDMR on *C. echinatus* (~36%), which was unsatisfactorily controlled (< 80%).

For *U. decumbens*, there was interaction between factors for visual control, while for SDMR there was interaction in statistical breakdown (Table 2). At 35 DAE, *U. decumbens* was controlled by most of the treatments but amicarbazone, regardless of the presence of straw. This species was unsatisfactorily controlled (<80%) when spraying imazapic and clomazone on 8 t ha^{-1} and indaziflam on 6 t ha^{-1} straw (Table 2).

Except for amicarbazone, all treatments increased the control of *U. decumbens* on 0 and 2 t ha^{-1} straw. Imazapic, isoxaflutole, tebuthiuron, amicarbazone + tebuthiuron and s-metolachlor + [diuron + hexazinone] stood out and reached 90% control. The control efficiency of amicarbazone decreased as the straw amounts increased. Amicarbazone, clomazone, imazapic, sulfentrazone, and indaziflam + metribuzin were statistically similar in results and promoted control efficiency and SDMR on average below 88 and 95%, respectively.

All treatments showed a low herbicide interception when applied on 10 t ha^{-1} straw. For *U. decumbens*, all treatments differed statistically from the control, both for control efficiency and SDMR. Amicarbazone promoted low SDMR values in *U. decumbens* on 6 and 8 t ha^{-1} straw.

The use of clomazone, isoxaflutole and s-metolachlor + [diuron + hexazinone] provided differential susceptibility among the Convolvulaceae species studied. Although spraying clomazone and isoxaflutole on 6, 8 and 10 t ha^{-1} straw reduced *M. aegyptia* control efficiency, both herbicides were effective in controlling this species, just as s-metolachlor + [diuron + hexazinone].

For *M. aegyptia*, there was interaction between factors for visual control, while for SDMR there was interaction in statistical breakdown (Table 3). At 35 DAE, *M. aegyptia* was sensitive to many of the herbicides tested. On 2, 6, 8 and 10 t ha^{-1} straw, imazapic proved to be unfeasible for *M. aegyptia* control. For all straw amounts and bare soil, the mixtures amicarbazone + tebuthiuron, s-metolachlor + [diuron + hexazinone] and indaziflam + metribuzin were efficient to control *M. aegyptia* at 35 DAE. This can be proved because these treatments remained within a statistical group of greater control efficiency under all conditions studied. The mixture [indaziflam + isoxaflutole] was also an efficient option for *M. aegyptia* control, except on 6 and 8 t ha^{-1} straw amounts. The highest sugarcane straw amounts (8 and 10 t ha^{-1}) intercepted more imazapic, resulting in poor control efficiencies (< 80%).

Table 1: Visual control (%) and shoot dry mass reduction (SDMR) (%) of *Cenchrus echinatus* under increasing sugarcane straw amounts at 35 days after emergence (DAE) of plants in control treatment

Visual control (%) of *Cenchrus echinatus* at 35 DAE					
Treatment	Amount of straw (t ha⁻¹)				
	0	2	6	8	10
Control	0.0 cA	0.0 cA	0.0 cA	0.0 dA	0.0 cA
Amicarbazone	55.0 bB	67.5 bA	37.5 bB	43.7 cB	53.7 bB
Clomazone	100.0 aA	99.5 aA	86.2 aB	76.2 bB	98.2 aA
Imazapic	97.0 aA	97.0 aA	95.7 aA	93.2 aA	95.2 aA
Indaziflam	94.5 aA	93.7 aA	90.0 aA	98.5 aA	78.7 bB
Isoxaflutole	97.7 aA	98.2 aA	96.5 aA	77.5 bB	88.7 aA
Sulfentrazone	72.5 bA	62.5 bA	57.5 bA	61.2 bA	62.5 bA
Tebuthiuron	94.5 aA	61.2 bB	55.0 bB	85.7 bA	63.7 bB
Amicarbazone + Tebuthiuron	96.5 aA	91.2 aA	91.5 aA	92.2 aA	92.0 aA
S-metolachlor + [Diuron + Hexazinone]	93.7 aA	99.5 aA	97.2 aA	97.7 aA	94.0 aA
[Indaziflam + Isoxaflutole]	100.0 aA	99.5 aA	98.5 aA	97.5 aA	93.2 aA
Indaziflam + Metribuzin	100.0 aA	100.0 aA	98.7 aA	97.0 aA	97.7 aA
CV (%)			13.9		
F			Factor A** Factor B** Interaction A×B**		
SDMR (%) of *Cenchrus echinatus* at 35 DAE					
Control	0.0 dA	0.0 cA	0.0 cA	0.0 dA	0.0 dA
Amicarbazone	77.5 bA	75.9 aA	43.8 bB	58.0 bB	66.2 bB
Clomazone	100.0 aA	100.0 aA	81.2 aB	64.8 bB	99.6 aA
Imazapic	94.0 aA	95.3 aA	91.6 aA	94.9 aA	86.4 aA
Indaziflam	97.1 aA	98.6 aA	92.9 aA	99.0 aA	89.3 aA
Isoxaflutole	97.6 aA	93.6 aA	95.3 aA	91.5 aA	82.3 aA
Sulfentrazone	45.0 cA	40.2 bA	40.2 bA	18.1 cA	35.7 cA
Tebuthiuron	86.4 bA	46.2 bB	62.4 bB	67.1 bB	60.4 bB
Amicarbazone + Tebuthiuron	92.4 bA	96.5 aA	94.5 aA	94.9 aA	94.4 aA
S-metolachlor + [Diuron + Hexazinone]	87.8 aA	100.0 aA	94.6 aA	96.0 aA	80.4 aA
[Indaziflam + Isoxaflutole]	100.0 aA	100.0 aA	100.0 aA	97.1 aA	88.7 aA
Indaziflam + Metribuzin	100.0 aA	100.0 aA	99.0 aA	96.6 aA	97.8 aA
CV (%)			17.9		
F			Factor A** Factor B** Interaction A×B[1]		

CV (%): coefficient of variation; Factor A: treatments; Factor B: sugarcane straw amounts. ** significant, [1]significant in the statistical breakdown and NS non-significant at 5% probability by the F-test; For statistical analysis, the data were transformed into $\mathrm{arc\ sen}\sqrt[2]{x/100}$, but the data in the table are the original ones. Means followed by the same letters, lowercase in the column and uppercase in the line, do not differ from each other by the Scott-Knott test at 5% significance. Source: The authors

Table 2: Visual control (%) and shoot dry mass reduction (SDMR) (%) of *Urochloa decumbens* under increasing sugarcane straw amounts at 35 days after emergence (DAE) of plants in control treatment

Visual control (%) of *Urochloa decumbens* at 35 DAE					
Treatment	Amount of straw (t ha⁻¹)				
	0	2	6	8	10
Control	0.0 cA	0.0 cA	0.0 dA	0.0 cA	0.0 dA
Amicarbazone	37.5 bA	52.5 bA	32.5 cA	67.5 bA	51.2 cA
Clomazone	100.0 aA	100.0 aA	83.8 bB	77.5 bB	88.8 bB
Imazapic	100.0 aA	98.8 aA	92.5 aB	65.0 bC	83.8 bB
Indaziflam	100.0 aA	100.0 aA	73.8 bB	96.2 aA	81.2 bB
Isoxaflutole	100.0 aA	96.2 aA	97.5 aA	97.5 aA	98.8 aA
Sulfentrazone	100.0 aA	90.0 aB	81.2 bB	81.2 bB	100.0 aA
Tebuthiuron	95.0 aA	92.5 aA	93.8 aA	96.2 aA	95.0 aA
Amicarbazone + Tebuthiuron	100.0 aA	97.5 aA	97.5 aA	97.5 aA	98.8 aA
S-metolachlor + [Diuron + Hexazinone]	100.0 aA	95.0 aA	98.8 aA	96.2 aA	90.0 bA
[Indaziflam + Isoxaflutole]	100.0 aA	100.0 aA	97.5 aA	92.5 aA	95.0 aA
Indaziflam + Metribuzin	100.0 aA	100.0 aA	86.2 bB	87.5 bB	96.2 aB
CV (%)	14.8				
F	Factor A** Factor B** Interaction A × B**				
SDMR (%) of *Urochloa decumbens* at 35 DAE					
Control	0.0 cA	0.0 cA	0.0 cA	0.0 cA	0.0 bA
Amicarbazone	72.6 bA	91.0 aA	61.1 bA	86.8 bA	70.5 aA
Clomazone	100.0 aA	100.0 aA	91.0 bB	88.6 bB	92.7 aB
Imazapic	100.0 aA	100.0 aA	93.5 bA	87.0 bA	96.0 aA
Indaziflam	100.0 aA	100.0 aA	94.3 bA	100.0 aA	91.87 aA
Isoxaflutole	100.0 aA	100.0 aA	100.0 aA	100.0 aA	100.0 aA
Sulfentrazone	100.0 aA	100.0 aA	91.0 bB	88.6 bB	92.7 aB
Tebuthiuron	61.0 bB	72.4 bB	87.8 bA	65.0 bB	87.8 aA
Amicarbazone + Tebuthiuron	100.0 aA	100.0 aA	100.0 aA	100.0 aA	97.6 aA
S-metolachlor + [Diuron + Hexazinone]	100.0 aA	100.0 aA	100.0 aA	93.5 aA	91.9 aA
[Indaziflam + Isoxaflutole]	100.0 aA	100.0 aA	100.0 aA	96.7 aA	100.0 aA
Indaziflam + Metribuzin	100.0 aA	100.0 aA	100.0 aA	100.0 aA	97.6 aA
CV (%)			13.6		
F			Factor A** Factor B^{NS} Interaction A×B[1]		

CV (%): coefficient of variation; Factor A: treatments; Factor B: sugarcane straw amounts. ** significant, [1]significant in the statistical breakdown and NS non-significant at 5% probability by the F-test; For statistical analysis, the data were transformed into $\mathrm{arc\ sen}\sqrt[2]{x/100}$, but the data in the table are the original ones. Means followed by the same letters, lowercase in the column and uppercase in the line, do not differ from each other by the Scott-Knott test at 5% significance. Source: The authors

Table 3: Visual control (%) and shoot dry mass reduction (SDMR) (%) of *Merremia aegyptia* (IPOPE) under increasing sugarcane straw amounts at 35 days after emergence (DAE) of plants in control treatment

Visual control (%) of *Merremia aegyptia* at 35 DAE					
Treatment	Amount of straw (t ha^{-1})				
	0	2	6	8	10
Control	0.0 cA	0.0 Da	0.0 cA	0.0 dA	0.0 dA
Amicarbazone	100.0 aA	100.0 aA	100.0 aA	98.7 aA	100.0 aA
Clomazone	98.75 aA	95.0 bA	92.5 bB	85.0 bB	85.0 bB
Imazapic	81.25 bA	85.0 cA	80.0 bA	76.2 cA	62.5 cB
Indaziflam	98.75 aA	87.5 cC	92.5 bB	71.2 cD	86.2 bC
Isoxaflutole	98.75 aA	93.7 bB	90.0 bB	88.7 bB	90.0 bB
Sulfentrazone	100.0 aA	98.7 aA	98.25 aA	99.5 aA	98.25 aA
Tebuthiuron	100.0 aA	100.0 aA	100.0 aA	100.0 aA	100.0 aA
Amicarbazone + Tebuthiuron	100.0 aA	100.0 aA	99.5 aA	100.0 aA	100.0 aA
S-metolachlor + [Diuron + Hexazinone]	100.0 aA	100.0 aA	98.75 aA	100.0 aA	100.0 aA
[Indaziflam + Isoxaflutole]	99.5 aA	98.25 aA	89.5 bB	88.7 bB	93.75 aA
Indaziflam + Metribuzin	100.0 aA	100.0 aA	100.0 aA	99.0 aA	100.0 aA
CV (%)	8.1				
F	Factor A** Factor B** Interaction A×B**				
SDMR (%) of *Merremia aegyptia* at 35 DAE					
Control	0.0 cA	0.0 dA	0.0 dA	0.0 dA	0.0 eA
Amicarbazone	100.0 aA	100.0 aA	100.0 aA	100.0 aA	100.0 aA
Clomazone	97.8 aA	95.1 aA	81.3 bB	76.5 cB	69.3 bB
Imazapic	33.8 bB	56.0 cA	35.89 cB	63.1 cA	21.2 dB
Indaziflam	94.7 aA	78.7 bB	87.1 bA	58.2 cB	54.7 cB
Isoxaflutole	99.6 aA	92.5 aA	83.6 bA	88.89 bA	82.7 bA
Sulfentrazone	100.0 aA	94.2 aA	96.4 aA	100.0 aA	93.3 aA
Tebuthiuron	100.0 aA	100.0 aA	100.0 aA	100.0 aA	100.0 aA
Amicarbazone + Tebuthiuron	100.0 aA	100.0 aA	100.0 aA	100.0 aA	100.0 aA
S-metolachlor + [Diuron + Hexazinone]	100.0 aA	100.0 aA	100.0 aA	100.0 aA	100.0 aA
[Indaziflam + Isoxaflutole]	100.0 aA	97.3 aA	85.8 bA	89.3 bA	95.5 aA
Indaziflam + Metribuzin	100.0 aA	98.7 aA	100.0 aA	100.0 aA	100.0 aA
CV (%)	15.5				
F	Factor A** Factor B** Interaction A×B[1]				

CV (%): coefficient of variation; Factor A: treatments; Factor B: sugarcane straw amounts. ** significant, [1]significant in the statistical breakdown and NS non-significant at 5% probability level by the F-test; For statistical analysis, the data were transformed into $\text{arc sen} \sqrt[2]{x/100}$, but the data in the table are the original ones. Means followed by the same letters, lowercase in the column and uppercase in the line, do not differ from each other by the Scott-Knott test at 5% significance. Source: The authors

Regardless of the sugarcane straw (0–10 t ha^{-1}), amicarbazone, isoxaflutole, sulfentrazone, tebuthiuron, amicarbazone + tebuthiuron, s-metolachlor + [diuron + hexazinone], [indaziflam + isoxaflutole] and indaziflam + metribuzin did not show significant differences for SDMR in *M. aegyptia* at 35 DAE (Table 3). The same was observed in the control treatment, whose efficiency was satisfactory (> 80%) regardless of the straw presence.

By contrast, spraying clomazone on 0 or 2 t ha^{-1} straw and indaziflam on 6 t ha^{-1} straw were more effective to reduce SDM of *M. aegyptia* than on the other straw amounts. Imazapic had a poor performance in terms of SDMR, with reductions below 43%.

For *D. horizontalis*, there was an interaction between factors for visual control (%) and SDMR (Table 4). Sulfentrazone and tebuthiuron were not efficient in controlling *D. horizontalis* (equal to or greater than 80%), regardless of the presence of straw (Table 4). Given their high solubilities (490 mg L^{-1} sulfentrazone; 2570 mg L^{-1} tebuthiuron), these herbicides require less water to be released from straw into the soil and hence control weeds.

Both amicarbazone and imazapic were inefficient in control efficiency and showed differences among 2, 8 and 10 t ha^{-1} straw amounts (Table 4). In turn, some remarks can be made for clomazone and isoxaflutole, which were efficient against *D. horizontalis* in straw absence. However, on 10 t ha^{-1} straw, the same herbicides promoted a control of about 65%, yet not efficient.

Regarding the application of molecules in isolation, indaziflam stood out in controlling *D. horizontalis* at 35 DAE. Statistical differences were observed between straw absence and presence, with all straw amounts reducing control efficiency when compared to 0 t ha^{-1}. Even so, the control of *D. horizontalis* by indaziflam was satisfactory (>80%) in all scenarios (Ghirardello *et al.* 2021).

Amicarbazone + tebuthiuron, s-metolachlor + [diuron + hexazinone], [indaziflam + isoxaflutole], and indaziflam + metribuzin were effective in controlling *D. horizontalis* when applied directly to the soil or on 2 t ha^{-1} straw (Table 4). When sprayed on 6, 8 and 10 t ha^{-1} straw, s-metolachlor + [diuron + hexazinone] and indaziflam + metribuzin were satisfactorily efficient (> 80%). By spraying [indaziflam + isoxaflutole], there was interactions with straw amounts, with results statistically equal between 0 and 2 t ha^{-1} (satisfactory), as well as among 6, 8 and 10 t ha^{-1} (unsatisfactory).

Table 4: Visual control (%) and shoot dry mass reduction (SDMR) (%) of *Digitaria horizontalis* under increasing sugarcane straw amounts at 35 days after emergence (DAE) of plants in control treatment

Visual control (%) of *Digitaria horizontalis* at 35 DAE					
Treatment	Amount of straw (t ha^{-1})				
	0	2	6	8	10
Control	0.0 dA	0.0 dA	0.0 cA	0.0 dA	0.0 dA
Amicarbazone	86.2 cA	68.7 cB	60.0 bB	32.5 cC	46.2 cC
Clomazone	100.0 aA	95.0 aA	78.7 aB	81.2 aB	65.0 bB
Imazapic	91.2 bA	78.7 bB	63.7 bB	67.5 bB	68.7 bB
Indaziflam	100.0 aA	90.0 aB	85.0 aB	83.2 aB	83.7 aB
Isoxaflutole	92.5 bA	78.7 bB	80.0 aA	84.5 aA	66.2 bB
Sulfentrazone	73.7 cA	63.7 cA	62.5 bA	77.5 aA	71.2 bA
Tebuthiuron	70.0 cA	53.7 cA	55.0 bA	55.0 bA	36.2 cA
Amicarbazone + Tebuthiuron	100.0 aA	98.2 aA	92.5 aA	78.7 aB	86.2 aB
S-metolachlor + [Diuron + Hexazinone]	100.0 aA	100.0 aB	86.2 aB	85.0 aB	91.2 aB
[Indaziflam + Isoxaflutole]	96.2 bA	85.0 bA	71.2 bB	63.7 bB	53.7 cB
Indaziflam + Metribuzin	100.0 aA	100.0 aA	92.5 aB	85.0 aB	80.0 aB
CV (%)	14.7				
F	Factor A** Factor B** Interaction A × B**				
SDMR (%) of *Digitaria horizontalis* at 35 DAE					
Control	0.0 cA	0.0 cA	0.0 dA	0.0 cA	0.0 cA
Amicarbazone	93.4 bA	68.7 bB	72.4 bB	58.5 bB	68.0 bB
Clomazone	100.0 aA	97.4 aA	47.8 cB	62.5 bB	42.5 bB
Imazapic	92.4 bA	78.1 bA	47.2 cB	69.4 bB	66.7 bB
Indaziflam	100.0 aA	90.5 aA	87.8 aB	74.0 aB	79.6 aB
Isoxaflutole	94.4 bA	62.6 bB	77.8 bA	83.0 aA	59.2 bB
Sulfentrazone	82.6 bA	64.8 bB	54.3 cB	81.7 aA	54.0 bB
Tebuthiuron	92.2 bA	68.5 bB	71.8 bB	64.8 bB	55.4 bB
Amicarbazone + Tebuthiuron	100.0 aA	99.9 aA	98.1 aA	86.4 aB	87.1 aB
S-metolachlor + [Diuron + Hexazinone]	100.0 aA	100.0 aA	88.9 aB	83.0 aB	90.0 aB
[Indaziflam + Isoxaflutole]	92.5 bA	60.7 bB	48.2 cB	51.3 bB	42.6 bB
Indaziflam + Metribuzin	100.0 aA	100.0 aA	92.5 aB	91.5 aB	73.1 aB
CV (%)			18.6		
F			Factor A** Factor B** Interaction A× B**		

CV (%): coefficient of variation; Factor A: treatments; Factor B: sugarcane straw amounts. ** significant and NS non-significant at 5% probability by the F-test; For statistical analysis, the data were transformed into $\arcsin \sqrt[2]{x/100}$, but the data in the table are the original ones. Means followed by the same letters, lowercase in the column and uppercase in the line, do not differ from each other by the Scott-Knott test at 5% significance. Source: The authors

We observed that indaziflam + metribuzin was efficient in control and SDMR against *D. horizontalis*. At 75 + 960 g ai ha^{-1}, this herbicide was satisfactorily efficient (> 80%) against *Chloris polydactyla* and *Eleusine indica* (Poaceae family) as sugarcane straw amounts increased (0, 1, 2 and 4 t ha^{-1}) and after rainfall simulations at 1 and 10 DAA (Malardo *et al.* 2017).

Regardless of the straw amount, the highest SDMR values (above 83%) were observed for amicarbazone + tebuthiuron, s-metolachlor + [diuron + hexazinone], and indaziflam + metribuzin, except for indaziflam + metribuzin on 10 t ha^{-1}. When compared to 0 t ha^{-1}, amicarbazone, clomazone, imazapic, indaziflam, tebuthiuron and [indaziflam + isoxaflutole] differed statistically from application on 2 t ha^{-1}, reducing SDM by less than 80% for *D. horizontalis*. Such result demonstrates herbicide retention by straw and consequent reduction in its control efficiency.

When sprayed on 6, 8 and 10 t ha^{-1} straw, clomazone had the lowest SDMR values, which were of 47.8, 62.5, and 42.6%, respectively, when compared to the 100% SDMR on 0 t ha^{-1}. Such a loss in control efficiency of clomazone (Gamit 360 CS) applied directly to the soil and sugarcane straw (5 t ha^{-1}) has already been reported against *U. decumbens* and *P. maximum* (26.25% and 13.75%, respectively) in a study under similar conditions (Tropaldi *et al.* 2018).

For *I. triloba*, there was an interaction between factors for visual control (%) and SDMR (Table 5). Regarding the control of *I. triloba*, spraying [indaziflam + isoxaflutole] directly to the soil or on the straw amounts evaluated did not differ statistically from the control, except for applications on 8 t ha^{-1}. However, this weed species was unsatisfactorily controlled (<80%), regardless of the straw cover condition (Table 5).

Spraying indaziflam, tebuthiuron, amicarbazone + tebuthiuron, sulfentrazone, and indaziflam + metribuzin on 0 t ha^{-1} straw showed satisfactory control efficiencies and SDMR values against *I. triloba*. This group of herbicides differs statistically from the other treatments, which, in turn, differed from the control and [indaziflam + isoxaflutole], promoting control efficiencies below 69%.

Ipomoea triloba was satisfactorily controlled by amicarbazone sprayed on all straw amounts, but not when applied directly to the soil (control below 64%). Using the same dose of amicarbazone on 0 or 5 t ha^{-1} sugarcane straw, with subsequent simulation of 30 mm rain at 1 DAA, increased the control efficiency of *Ipomoea*

Table 5: Visual control (%) and shoot dry mass reduction (SDMR) (%) of *Ipomoea triloba* under increasing sugarcane straw amounts at 35 days after emergence (DAE) of plants in control treatment

Treatment	Amount of straw (t ha^{-1})				
	0	2	6	8	10
Visual control (%) of *Ipomoea triloba* at 35 DAE					
Control	0.0 cA	0.0 bA	0.0 cA	0.0 cA	0.0 cA
Amicarbazone	63.7 bB	95.0 aA	95.0 aA	92.5 aA	97.5 aA
Clomazone	33.7 bA	57.5 aA	35.0 bA	36.2 bA	16.2 cA
Imazapic	68.7 bA	95.7 aA	92.5 aA	95.0 aA	94.5 aA
Indaziflam	100.0 aA	98.7 aA	73.7 aB	72.5 bB	56.2 bB
Isoxaflutole	50.0 bA	28.7 bA	15.0 cA	43.7 bA	55.0 bA
Sulfentrazone	100.0 aA	100.0 aA	97.5 aA	98.2 aA	96.2 aA
Tebuthiuron	92.5 aA	98.7 aA	100.0 aA	100.0 aA	92.7 aA
Amicarbazone + Tebuthiuron	97.5 aA	90.0 aA	97.5 aA	100.0 aA	100.0 aA
S-metolachlor + [Diuron + Hexazinone]	26.2 bA	13.7 bA	36.2 bA	36.2 bA	41.2 bA
[Indaziflam + Isoxaflutole]	10.0 cA	10.0 bA	10.0 cA	35.0 bA	10.0 cA
Indaziflam + Metribuzin	100.0 aA	100.0 aA	37.5 bB	55.0 bB	38.7 bB
CV (%)	30.2				
F	Factor A** Factor B^{NS} Interaction A × B**				
SDMR (%) of *Ipomoea triloba* at 35 DAE					
Control	0.0 cA	0.0 dA	0.0 eA	0.0 cA	0.0 dA
Amicarbazone	47.7 bB	91.2 aA	99.3 aA	97.2 aA	97.4 aA
Clomazone	53.2 bA	58.6 bA	61.7 bA	56.2 bA	69.1 bA
Imazapic	92.4 aA	97.8 aA	98.7 aA	98.8 aA	97.2 aA
Indaziflam	100.0 aA	97.8 aA	84.5 bA	73.4 bB	42.9 cB
Isoxaflutole	86.5 aA	69.1 bB	47.7 cB	67.0 bB	88.3 bA
Sulfentrazone	100.0 aA	100.0 aA	98.6 aA	100.0 aA	98.6 aA
Tebuthiuron	98.6 aA	99.9 aA	100.0 aA	100.0 aA	97.4 aA
Amicarbazone + Tebuthiuron	99.9 aA	83.4 aA	99.0 aA	100.0 aA	100.0 aA
S-metolachlor + [Diuron + Hexazinone]	55.7 bA	66.4 bA	64.1 bA	68.9 bA	71.0 bA
[Indaziflam + Isoxaflutole]	18.0 cB	26.6 cB	23.6 dB	57.1 bA	37.2 cA
Indaziflam + Metribuzin	100.0 aA	100.0 aA	73.2 bB	79.1 bB	81.0 bB
CV (%)	21.9				
F	Factor A** Factor B^{NS} Interaction A × B**				

CV (%): coefficient of variation; Factor A: treatments; Factor B: sugarcane straw amounts. ** significant and ^{NS} non-significant at 5% probability level by the F-test; For statistical analysis, the data were transformed into $\text{arc sen} \sqrt[2]{x/100}$, but the data in the table are the original ones. Means followed by the same letters, lowercase in the column and uppercase in the line, do not differ from each other by the Scott-Knott test at 5% significance. Source: The authors

grandifolia at 28 DAA (Toledo *et al.* 2009).

The mixture indaziflam + metribuzin applied directly to the soil or on 2 t ha^{-1} straw showed statistically equal results and high SDMR against *I. triloba* (above 91%). However, on 6, 8, or 10 t ha^{-1} straw, which were statistically equal, such reductions were below 81%.

Discussion

Sulfentrazone could poorly control *C. echinatus* (< 80%), given its low SDMR. It has already been noticed (Niz *et al.* 2018) despite its registration against that species. Conversely, imazapic was highly efficient against *C. echinatus* control, regardless of the straw presence. This result corroborates other study using 20 t ha^{-1} straw and receiving the same rainfall input as that in our study (10 mm) against *Cyperus rotundus* (Simoni *et al.* 2006). Despite the efficient of imazapic against other Poaceae species (e.g., *U. decumbens*, *U. plantaginea*, *D. horizontalis*, *Eleusine indica* and *P. maximum*, *C. echinatus*), it has not been mentioned in the literature yet (Rodrigues and Almeida 2018).

After 42 days of rain simulation (10-, 20- and 40-mm depths), indaziflam + isoxaflutole sprayed directly to the soil or on sugarcane straw (10 t ha^{-1}) provided a high control of *P. maximum* (Malardo 2019). Indaziflam and isoxaflutole have already been reported as efficient against *D. horizontalis*, in the absence of sugarcane straw (Tropaldi *et al.* 2018; Ghirardello *et al.* 2021). In our study, this pre-formulated mixture also proved to be efficient in pre-emergence control of *C. echinatus* under all conditions evaluated. One reason for that relies on the solubility (0.0028 kg m^{-3} at 20°C) and log Kow (2.8 at pH 4, 7 and 9) of indaziflam, which is classified as slightly or moderately soluble in fat. Notably, Poaceae species are highly sensitive to indaziflam (Silva *et al.* 2009; Dias *et al.* 2019; Ghirardello *et al.* 2021).

According to the package inserts of the commercial products used in this study (except Provence Total [indaziflam + isoxaflutole]), spraying on bare soil can satisfactorily control *U. decumbens*. This species is known to be sensitive to isoxaflutole and indaziflam when applied alone (Rodrigues and Almeida 2018). However, in our study, it was also sensitive to the pre-formulated mixture [indaziflam + isoxaflutole], regardless of the straw presence at 35 DAE. At this time, control levels were adequate in our study, which has not been yet registered either in the package inserts or literature so far (AGROFIT 2021).

We also observed that amicarbazone had regular to adequate control levels against the Poaceae family (*U. decumbens*, *D. horizontalis* and *C. echinatus*), regardless of the straw presence. This result was highlighted by significant SDMR values in these plant species. Amicarbazone has its control efficiency increased with straw presence, in sprays after rain events, or applications direct to the soil (Negrisoli *et al.* 2007). This herbicide is broadleaf-specific for excellence and can be characterized as effective in controlling species such as *I. quamoclit*, *I. triloba*, and *M. cissoides*; however, other studies have shown a differential susceptibility among Convolvulaceae species (Campos *et al.* 2009; Nicolai *et al.* 2013; Ribeiro *et al.* 2018). Indeed, we only excellent control levels against *U. decumbens*.

The largest amounts of straw could intercept imazapic significantly, reducing the efficiency of *M. aegypita* control (< 80%). Toledo *et al*. (2009) observed different results when spraying 154 g ai ha^{-1} in pre-emergence onto straw after mechanized harvesting in a green sugarcane system on a sandy soil during the dry season. These authors observed an adequate control (> 80%) up to 120 days after application (DAA). We believe that such a difference with our results is due to molecule solubility (S = 2200 mg L^{-1}), which, after interacting with edaphoclimatic conditions under a rainy season, decreased the efficiency of the herbicide.

The high solubility (S = 4600 mg L^{-1}), vapor pressure (1.3 × 10^{-6} Pa at 25°C), and Kow (log Kow 1.23 at pH 7) of amicarbazone, along with the biology of *M. aegyptia*, may explain its control efficiency. Toledo *et al.* (2009) noted that a 30-mm rain simulation after 24 h application of amicarbazone (at the same dose as ours), directly to the soil or on 5 t ha^{-1} sugarcane straw, provided high control levels of *M. cissoides* at 28 DAA.

Regarding the dynamics of metribuzin in sugarcane straw, Rossi *et al.* (2013) reported that applications on 5 and 7.5 t ha^{-1} caused retentions of 90 and 100% by straw, respectively. Therefore, when applied on sugarcane straw, indaziflam and metribuzin tend to have similar poor performances due to their physicochemical properties. Moreover, large amounts of rainfall soon after application can improve the breaking of the barrier imposed by the straw, allowing the product to reach the soil.

The mixture of the herbicides indaziflam and isoxaflutole has already proved to be inefficient to control *I. triloba* (AGROFIT 2021). One study reported a satisfactory control (> 80%) of *I. heredifolia* by amicarbazone + tebuthiuron (910 + 900 g ai ha^{-1}) applied in pre-emergence on sugarcane straw (Bidoia *et al.* 2018). *Ipomoea* and *Merremia* species have shown a differential susceptibility to herbicides applied in pre-emergence during different dry periods (Ribeiro *et al.* 2018).

Reductions in control efficiency of isoxaflutole with increasing sugarcane straw amounts have already been reported in the literature. By evaluating the mobility and persistence of isoxaflutole (187.5 g a.i. ha^{-1}) on different soils and sugarcane straw amounts, Monquero *et al.* (2008) observed that, compared to applications directly to the soil, spraying on 10 and 15 t ha^{-1} straw amounts reduced the control efficiency against *Sorghum bicolor* by 15.5 and 17.5%, respectively, in clayey Latosols (SiBCS), and by 28.0 and 33.0%, respectively, in medium-texture Latosols (SiBCS), when the bioindicator was sown at 40 DAA.

Conclusion

Under the conditions of this study, the mixtures s-metolachlor + [diuron + hexazinone] and indaziflam + metribuzin are efficient in controlling *C. echinatus*, *U. decumbens*, *M. aegyptia*, and *D. horizontalis*, regardless of the straw cover conditions (0 to 10 t ha^{-1}), reducing their shoot dry masses by at least 80.4 and 73.1%, respectively. The species *I. triloba* and *D. horizontalis* are more tolerant to the herbicides tested in this study. Isoxaflutole is efficient against *D. horizontalis*. Lastly, sulfentrazone, tebuthiuron, and amicarbazone + tebuthiuron are efficient against *I. triloba*, regardless of the straw condition, reducing their shoot dry masses by at least 83.4%.

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Author Contributions

Paulo Henrique Vieira dos Santos: conceptualization, formal analysis, investigation, methodology development and writing of the original draft. Bruna Ferrari Schedenffedlt: formal analysis, writing and proofreading of the original draft. Patricia Andrea Monquero: provision of resources; writing, proofreading, and editing of the original draft and funding acquisition.

Conflicts of Interest

The authors declare no conflicts of interests among institutions.

Data Availability

This work does not involve animals hence.

Ethics Approval

Not applicable to this article.

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